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13. ABSTRACT *(Maximum 200 words)*

'Smart' Materials and Structures have the capability to respond to their environment to a significant degree, by virtue of intrinsic properties and/or built-in sensor/actuator systems. The words 'smart' or 'intelligent' as applied to materials/structures are used in an idealistic and imprecise way to indicate an analogy with the integrated sensor/actuator/control systems evolved by living beings. The programatic objectives of this proposal suggest the following definition of Smart Materials/Structures (SMS): Smart Materials / Structures (SMS) - Structural systems based upon materials with the ability to SENSE their own response to environmental and operational stimuli, and MODIFY that response in such as way as to maintain or optimize structural performance, utilizing embedded sensors and actuators interfaced with closed-loop ADAPTIVE CONTROL systems based on system stimulus-response models. In this effort, BDM Federal, Inc., a subsidiary of BDM International, Inc. (BDM) conducted a technical analysis of Smart Materials and Structures in order to assist DARPA in planning a future initiative in this area. The ultimate goal of Smart Materials/Structures is the development of smart subsystems, consisting of materials sensors, actuators, and controllers, etc., capable of significantly improving the performance of DoD systems.

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SMART MATERIALS / STRUCTURES
TECHNICAL ANALYSIS

FINAL REPORT

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1.0 OBJECTIVE

BDM International, Inc. (BDM) conducted a technical analysis of Smart Materials and Structures as illustrated in Figure 1.0-1. The ultimate goal of Smart Materials/Structures is the development of smart subsystems, consisting of the integration of materials, sensors, actuators, and controllers, etc., capable of significantly improving the performance of DoD systems.

2.0 SMART MATERIALS / STRUCTURES

2.1 INTRODUCTION

'Smart' Materials and Structures have the capability to respond to their environment to a significant degree, by virtue of intrinsic properties and/or built-in sensor/actuator systems. The words 'smart' or 'intelligent' as applied to materials/structures are used in an idealistic and imprecise way to indicate an analogy with the integrated sensor/actuator/control systems evolved by *living* beings (that need not necessarily be 'smart' or 'intelligent' in the normal usage of these words). The concept is thus amorphous and is better understood through examples, such as the reconfigurable structures concepts shown in Figure 2.1-1.

The pragmatic objectives of this proposal suggest the following definition of Smart Materials / Structures (SMS):

> ***Smart Materials / Structures (SMS)*** *- Structural systems based upon materials with the ability to SENSE their own response to environmental and operational stimuli, and MODIFY that response in such as way as to maintain or optimize structural performance, utilizing embedded sensors and actuators interfaced with closed-loop ADAPTIVE CONTROL systems based on system stimulus-response models.*

Smart Materials / Structures may potentially be utilized where application of control was previously prohibited due to the large number of actuators and sensors required. For example, a smart skin for a control surface, using piezoceramics or shape memory alloy tendons, can provide autonomous, distributed control of shape, and is accomplished with significant simplification of the system (e.g. elimination of moving parts, communication lines, and power distribution systems). Traditionally, space structures have been deployed via pyrotechnics, which are complex, often unreliable, and rather heavy. Prototype application of shape memory alloy for deploying space structures has reduced the weight required for these deployment mechanisms, improved reliability, and decreased the amount of transient vibration aboard spacecraft during deployment, which is critical for costly and sensitive payloads.

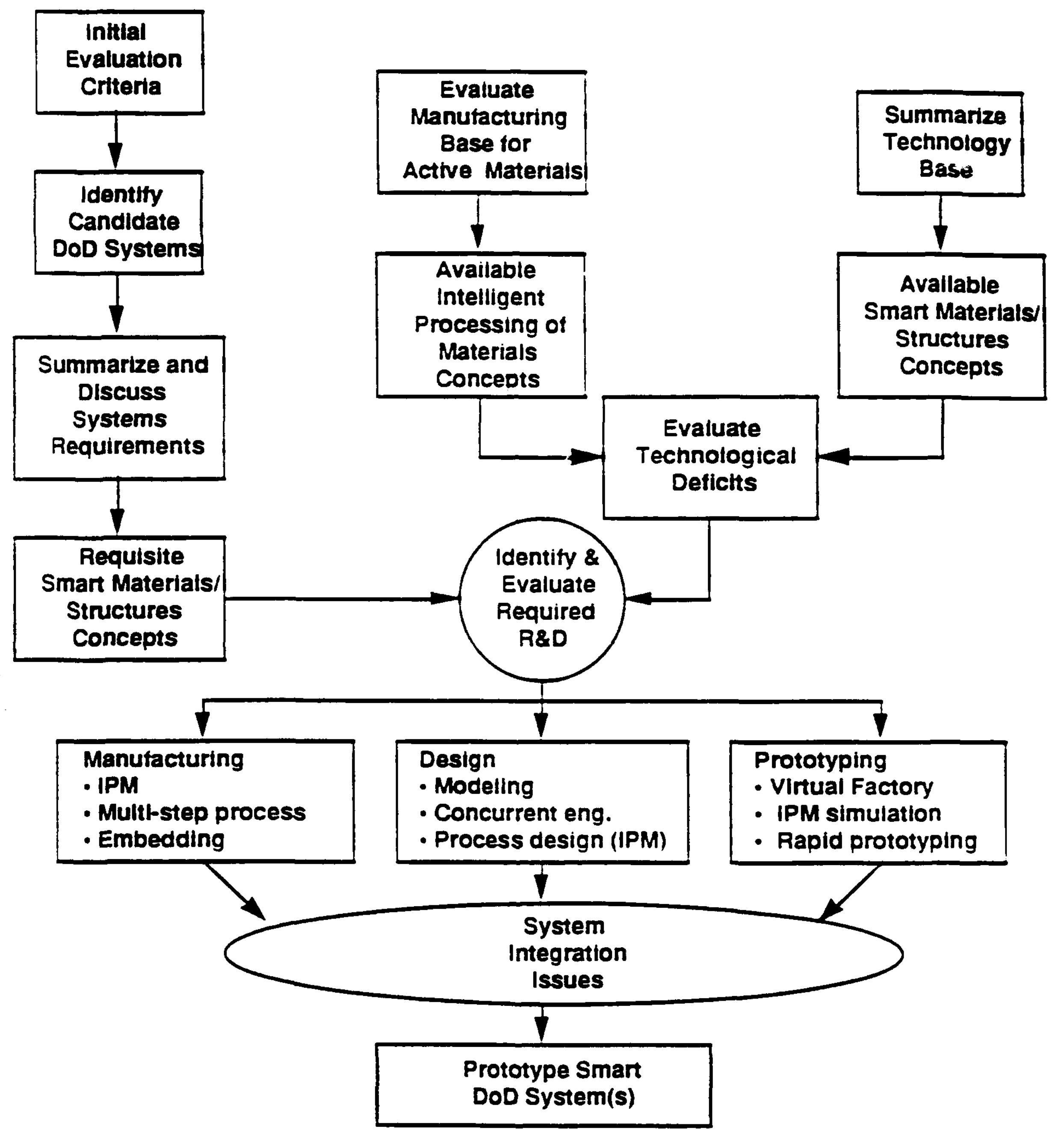


Figure 1.0-1. Flow chart of technical analysis for Smart Materials/Structures effort.

APPLICATION SPECIFIC RECONFIGURABLE STRUCTURES

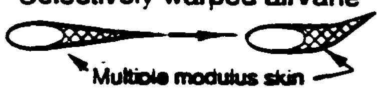
Technology Inputs

- Multiple modulus skins and structures
- Embedded digital microsensors
- Compact actuators with/without tendons
- High response microvalves
- Supporting control electronics

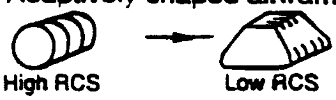
Lead to

Potential Applications

- Selectively warped airvane

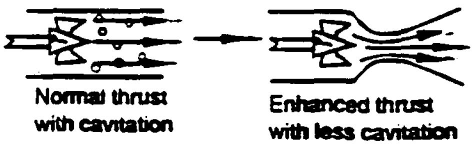


- Adaptively shaped airframe



- Altitude optimized wing

- Propeller shrouds



Potential Applications	Technology Discriminators	Payoffs
Wings and airvanes	• Embedded actuators and sensors • Multiple modulus structure • Real time optimized aerodynamics • Design simplicity	• More internal volume in missile body • Lower cost due to lower part counts and net shape molding processes • Less weight than conventional control systems • Multiplexing leads to greater reliability • Less drag leads to greater range and less specific fuel consumption
Adaptively shaped airframes	• Variable RCS • Frequency selective • Threat adaptive • Real time optimized aerodynamics • Embedded sensors and actuators	• Change reflecting angle with threat • Inflight tradeoffs between drag and RCS • Low cost • Less weight than many low signature spray-on systems
Propeller shrouds	• Optimized hydrodynamic shaping in real time • Less cavitation • Embedded sensors and actuators • Can be integrated into composite structures	• More speed • Quiet - less cavitation • Efficient reversing • Less drag and greater thrust

Figure 2.1-1: An example of a smart structure application.

SMS also allows sensing, actuation, and control to be implemented where traditional means of control was impractical. For example, a prototype of a soft machinery mount used to provide a microgravity vibration environment aboard a milligravity spacecraft was developed using piezoelectric film actuators [Mercadal, Blaurock, von Flotow, and Wereley, 1991]. The mount passively (that is, with no active control), provided adequate isolation of a payload above 1 Hz. The soft mount was actively controlled below 1Hz using multivariable control techniques to reduce low frequency vibrations (.1 to 1 Hz). Thus, even if the active elements failed in orbit, the passive mount was capable of providing baseline control adequate to assure mission success. This demonstrates the immensely improved functional versatility of the Smart Material/Structure system over what could be accomplished via traditional means.

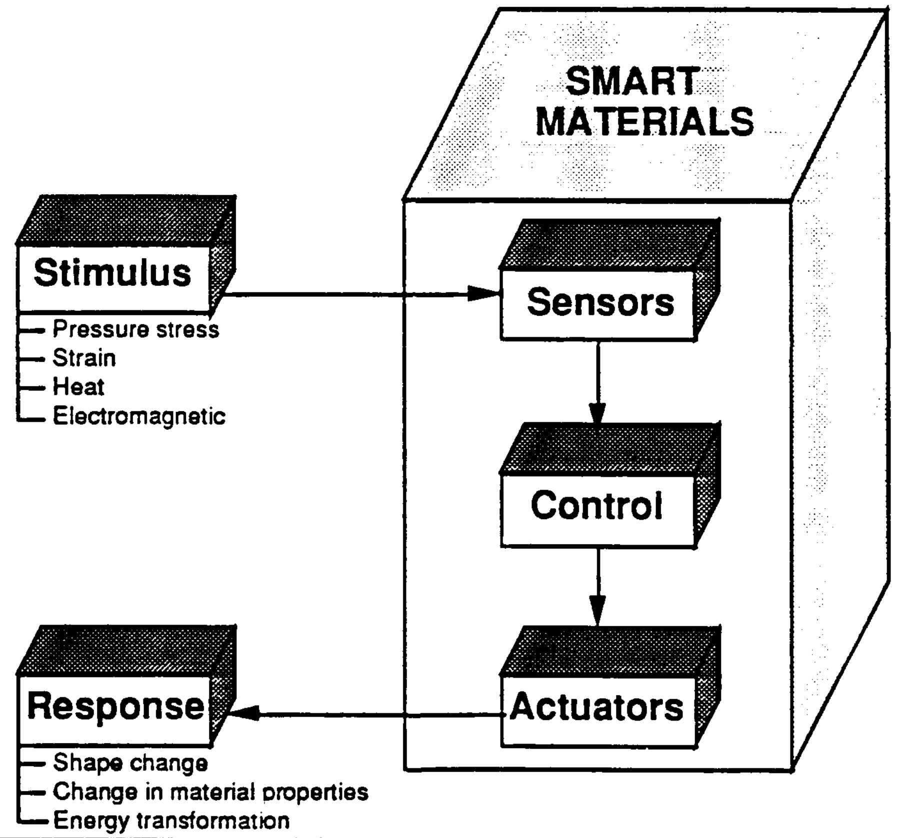


Figure 2.2-1: Smart materials/structures.

2.2 THE CURRENT TECHNOLOGY BASE

An important technology driver for SMS has been the space program, particularly in the areas of adaptive structures, vibration control, and health monitoring. Results obtained in this area cover a wide range of applications of DoD interest. An important example is the ACESA

(Advanced Composites with Embedded Sensors and Actuators) program being carried out by TRW and Boeing for AFSC. The ACESA program provides a useful overview of current smart technology and illustrates the methodology that should be exercised for evaluation of the utility of available technology for the demonstration system. As part of the ACESA program, a number of sensor and actuator candidates were identified as compatible with space systems applications as shown in Figure 2.2-1. These candidates were evaluated with respect to the general criteria listed in Table 2.

Descriptions of the operation of four actuators - piezoceramic, electro/magnetostrictive, shape memory alloy (SMA), and electro-rheological fluids, as well as evaluation of their potential, are given in Appendix A. The principal measure of interest to the ACESA program is strain. Out of the large number of fiber optic sensors (FOS) capable of measuring strain, only a few (listed in Table 1) were found suitable. Noisy and temperature-dependent response, introduction of cross-talk between sensor arms by multiplexing, and delicacy and difficulty of construction tend to offset their many positive attributes (strength, temperature stability, relative immunity to EMI, etc.). The evaluations of Table 1 are of interest for any application involving strain sensing. Tables 2 and 3 show the ACESA sensor and actuator selection matrix, respectively. While the requirements row is application-specific, the information shown for the various sensors and the actuators is generally applicable.

In order for the sensors and actuators to function as part of a smart system, they must be made an integral part of that system, typically by being embedded in a structural composite. TRW has evaluated several composites with respect to their suitability as embedding materials. Their results are given in Appendix B. In summary, we have very succinctly addressed the salient features of the current technology base and at the same time illustrated many of the important issues involved in lower half of the flow chart of Figure 1.0-1, in the context of the intelligent structures problem. Lest we give the impression that this area completely dominates the smart materials/structures arena, Appendix C lists a representative set of programs and research efforts in this area. This is then the reservoir from which a data base must be culled, similar to that put together by Boeing, bearing both on the applicability of current technology to a chosen DoD system, and on the additional required RD&E.

Table 1: Sensor and actuator candidates (from Ref. 3).

Active Material	Sensors	Actuators
Piezoelectric ceramics/films	✓	✓
Shape memory alloys (e.g. NiTiNOL)	✓	✓
Fiber optics	✓	
Acoustic waveguides	✓	
Capacitive sensors	✓	
X-ray sensors	✓	
Strain gages	✓	
Accelerometers	✓	
Electro-rheological fluids		✓
Magnetostrictive materials		✓
Electrostrictive material		✓

Table 2. Sensor selection evaluation matrix (from Ref. 3)

Sensor	Embedability	Technical Readiness	Max Temp [C]	Dynamic Range [micro--strain]	Bandwidth [Hz]	Sensitivity [microstrain]	Linearity	Networkable	Component Cost	Shock Sensitivity	EMI Sensitivity
Requirement	1/3	•	175	± 5	500	.2	•	•	Mod	Low	Low
Piezoelectric ceramic	1	•	560	200	20K	.001 - .01	•	•	Mod	Mod	Low
Fiber optic interferometer	1	•	300	2800	10K	.11 per fiber	•	•	Mod	Mod	Low
NiTiNOL wire	1	•	300	5000	10K	.1-1.0	•	•	Low	Low	Low
Strain gage	1	•	1112	10000	500K	2	•	•	Low	Low	Low

Table 3. Evaluation of embedded fiber optic strain sensing techniques (Ref. 2)

Parameter / Technology	Resolution Strain	Direction	Orthogonal Resolution	Embeddability	Cost	Complexity	Potential Problems
Phase Locked Loop	$\sim 10^{-7}$	No	No	Good	Very High	Lots of support equipment	
Mach Zehnder Interferometry	$< 10^{-8}$	Yes	Yes	Good	Low ~few $100/Ch.	Low	Fibers break Temp.
Few Mode	~10^- [illegible]	Only if 2 sensor used	Possibly	Good	TBD	TBD	Fibers break
Dual Core	3×10^{-5}	No	Yes	Difficult	High	High	Fibers break

2.3 INTELLIGENT PROCESSING OF MATERIALS

During this program, it was evident that a primary obstacle to DoD implementation of Smart Materials/Structures (SMS) concepts and prototypes was the lack of a manufacturing base for the active materials (e.g. electrostrictive ceramics, shape memory alloy, etc.) required for implementation, and of a manufacturing base for embedding the various sensor and actuator subsystems into composite material and other material systems. Results of an evaluation by TRW (shown in Appendix B) address the suitability of several composites with respect to the embedding materials.

The manufacturing base in active materials can be developed using the Intelligent Processing of Materials (IPM) paradigm for control of a material manufacturing process. IPM relies on the development of three enabling technologies including in-situ sensing of the process, modeling of the evolution of the process, and intelligent or adaptive control. Formally, the following definition is suggested for IPM:

> *Intelligent Processing of Materials (IPM) - Active, ADAPTIVE CONTROL of materials processing utilizing IN-PROCESS SENSING of critical microstructural, geometrical, and overall product features as they evolve during processing, utilizing analytical and heuristic MODELS of the process to MODIFY the process schedule (e.g. time histories of*

temperature, pressure, gas flow rates, etc.) as required during processing to achieve optimized, reproducible product goals.

A block diagram of an IPM system is shown in Figure 2.3-1. The basic goal of IPM is to develop a processing capability for engineered materials with specific properties. The need for smart composite materials that are engineered to have specific properties is substantial. For example, the effectiveness of piezoceramic composites could be improved by introducing an IPM system that examines the evolution of permittivity during processing, in order to maximize the permittivity of the final product. Alternatively, IPM could be applied to grow large diameter and highly crystallographic magnetostrictive crystals, so as to permit the implementation of actuators for high-force and low-displacement applications. Further, problems associated with the embedding of actuator or sensor components in a composite material could be resolved through the application of IPM, by using the embedded smart sensor/actuator as the in-process sensor, such as in the embedding of fiber optic sensors in a polymer composite.

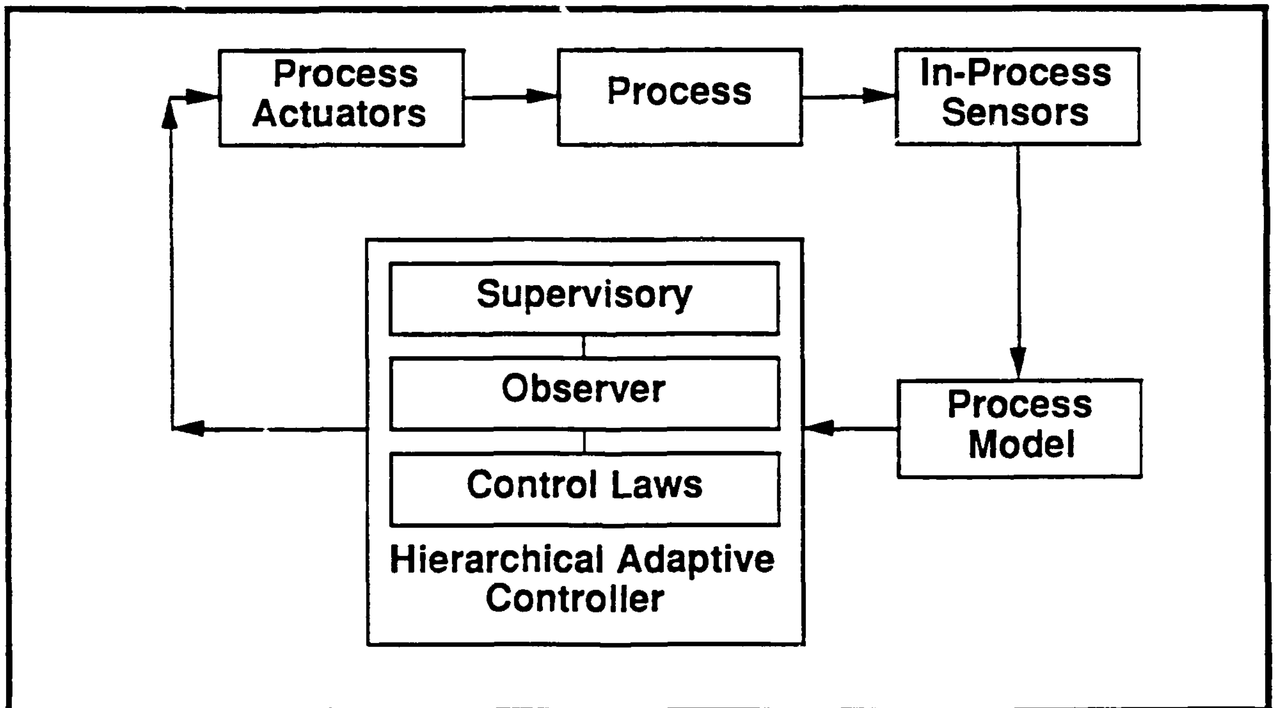


Figure 2.3-1. Block diagram implementation of Intelligent Processing of Materials paradigm using BDM's hierarchical adaptive control system architecture.

2.4 INTEGRATED IPM - SMS PROGRAM

An interesting aspect of both the SMS and IPM technology areas is the significant amount of overlap between the two. This overlap is illustrated in Figure 2.4-1.

BDM, as part of the successful team which bid on DARPA RA 92-15 on the topic area of Synthesis and Processing of Smart Materials (the team consists of Martin-Marietta, Lockheed, and AVX, along with university and government laboratory participation) seeks to accelerate the development of Smart Materials and Structures and transition them to existing and future military systems, but even more significantly, to transition these technologies to commercial applications. The ultimate vision of this industrial - academia - government lab Partnership is to develop a broadband smart material comprising two distinct actuator materials with operational capabilities at both the micro (micron) and macro (millimeter) scale, that can sense, respond, and cancel acoustic and vibrational energy.

The Partnership has the potential to have an immense impact on numerous military and commercial systems. In addition, the Partnership identified several technology insertion targets largely as identified by BDM under this program:

- Electro-optic (EO) targeting systems such as LANTIRN night vision system to enhance pointing resolution and precision

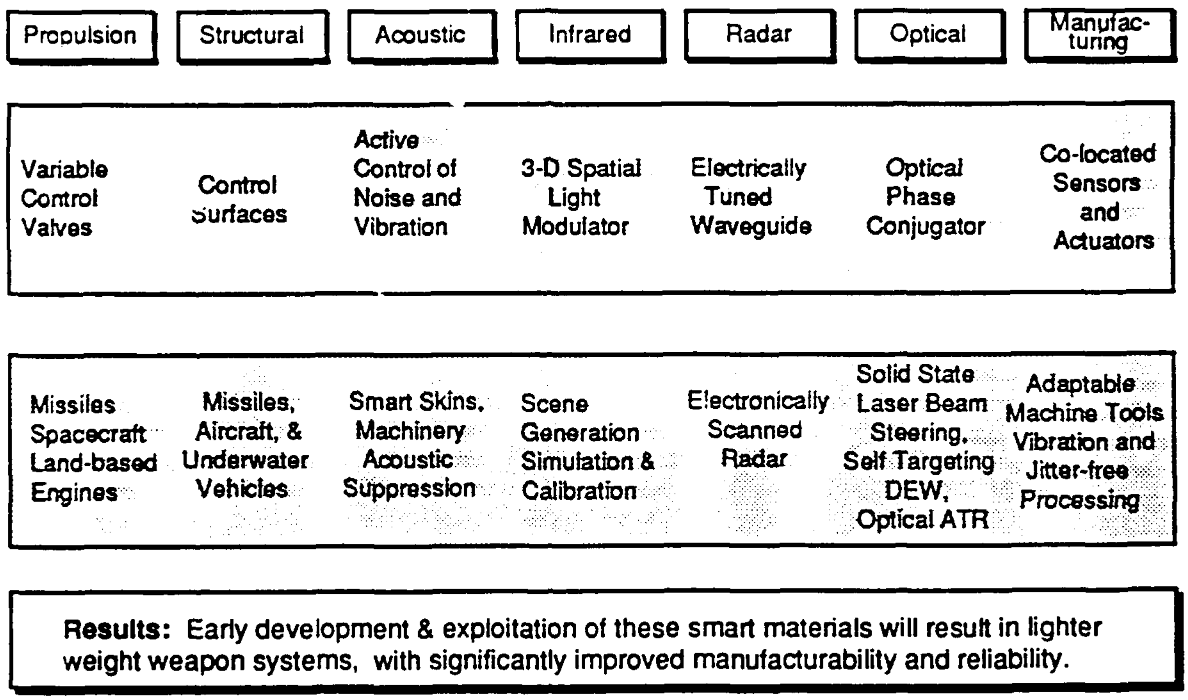


Figure 2.4-1. Pervasive impact of an integrated Intelligent Processing of Materials for Smart Materials Structures (IPM/SMS) Program on DoD systems.

- Fleet Ballistic Missile System for enhanced range and precision
- Advanced control surfaces for underwater vehicles
- Improved pointing and tracking control of large flexible space structures
- Isolation of engine / transmission noise from aerospace and aircraft structures in struts, pylons, etc.
- Development of jitter-free adaptive compliance precision machine tools
- Automotive engine mounts

A Technology Applications Board has been established under Lockheed chairmanship to define application requirements, encourage technology transfer, and facilitate participation in the program by outside users including other ARPA Partnerships. The Partnership identifies five major thrust areas:

- Synthesis and Processing of Multilayer Ceramic Actuators
- Synthesis and Processing of Shape Memory Foil
- Application of IPM to each process
- Integration of each actuator concept into a prototype, large-scale active vibration canceller
- Integration towards an active vibration canceller at the micron scale

Significant and early deliverables of a prototype AVC, a proof-of-principle device at the millimeter scale, and an IPM-based process are proposed at the end of an aggressive, 18 month, Phase I program.

3.0 SUMMARY OF SUBSTANTIVE INFORMATION FROM VISITS AND MEETINGS

BDM personnel participated in the DARPA–sponsored Workshop in Smart Materials / Structures in January, 1991. In conjunction with the University of California, Santa Barbara (UCSB) URI working group, a one-day workshop was organized by Dr. Tony Evans, UCSB, and Dr. Eric Cross, Penn State, and focused principally on the electromechanical behavior of piezoelectric (PZT and PZLT) ceramics and piezoelectric composites. Major gaps in knowledge about these materials were identified. First, the effects of processing on long-term stability of properties of piezoelectrics are were not fully characterized. Surface flaws induced during processing were shown to drastically affect useful lifetimes of these materials. The opportunities in Intelligent Processing of piezoelectric composites should be evaluated, where fibers have potential uses as structural elements, in-situ sensors during processing and in health monitoring of the composite during service life. Additionally, Dr. Bill Ditto of Naval Surface Weapons Center (NSWC), White Oak, Maryland, reviewed their efforts on magnetostrictive materials such as Terfenol, which exhibit substantial modulus shifts as a function of applied magnetic field, and

are envisioned in damping of mechanical vibrations in noise - sensitive applications aboard submarines and damping of vibrations in precision machining of optics and high speed bearings.

BDM personnel attended a Workshop on Smart Materials hosted by the Defense Sciences Research Council in La Jolla, California on 18 July 1991. Key presentations were made by several Government program managers, as well as by Dr. Uchino of Penn State, who spoke about commercialization of Smart Materials in Japan.

BDM personnel participated in the International Symposium and Exhibition on Active Materials and Adaptive Structures in Alexandria, Virginia, on 4-8 November 1991. A prototype smart materials/structures application was presented by Dr. N. M. Wereley (BDM) at the conference. This paper describes an ultrastable microgravity vibration isolation softmount for deployment in a space shuttle middeck locker that was developed using piezo-film actuators. Active control of low frequency vibrations (0.01 to 1 Hz), and passive isolation of high frequency vibrations, were experimentally verified, proving feasibility of the soft-mount concept. During this conference, substantial information was collected on smart materials/structures component technologies, as well as current research programs in potential DoD prototype system technologies.

BDM personnel met with Dr. Kristl Hathaway (ONR) to discuss the potentials for magnetostrictive materials for both sensor and actuator applications. It was recognized that magnetostrictive materials are in a somewhat embryonic stage of development. It was determined that a workshop on magnetostrictive materials - specifically manufacture of magnetostrictive crystal, potential DoD applications, and potential implementations could provide the impetus for technological innovation in magnetostrictive materials. A recent SPIE conference (February 1992) had a day-long workshop on magnetostrictive applications. BDM is exploring the potential for further workshops in order to derive the most benefit for DARPA/DSO.

BDM developed a conceptual design for a micromechanical magnetostrictive actuator. The concept involves using layered material to produce a magnetostrictive structure with improved crystal orientation in order to achieve 30 - 40% increase in strain due to an applied electromagnetic field. The actuator can then be used to improve the operating envelopes of micromechanical devices such as a micromechanical tuning fork gyroscope. The gyroscopic response of the micromechanical tuning fork to an input rate about the longitudinal axis between the tines has substantial stability problems at high frequency due to time periodic dynamics. Implementation of a micromechanical magnetostrictive actuator, with a suitable control algorithm, will allow the gyroscope to operate at higher frequencies than is currently possible. BDM is continuing to develop this concept.

4.0 LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED

No manuscripts were submitted or published under ARO sponsorship during this reporting period, including journal references.

5.0 SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED DURING THIS REPORTING PERIOD

The following scientific personnel were supported during the reporting period: Dr. P.A. Parrish, Dr. C.J. Coe, Dr. R.B. Raphael, Dr. Tony F. Zahrah, and Dr. Norman M. Wereley.

6.0 REPORT OF INVENTIONS (BY TITLE ONLY)

None to report.

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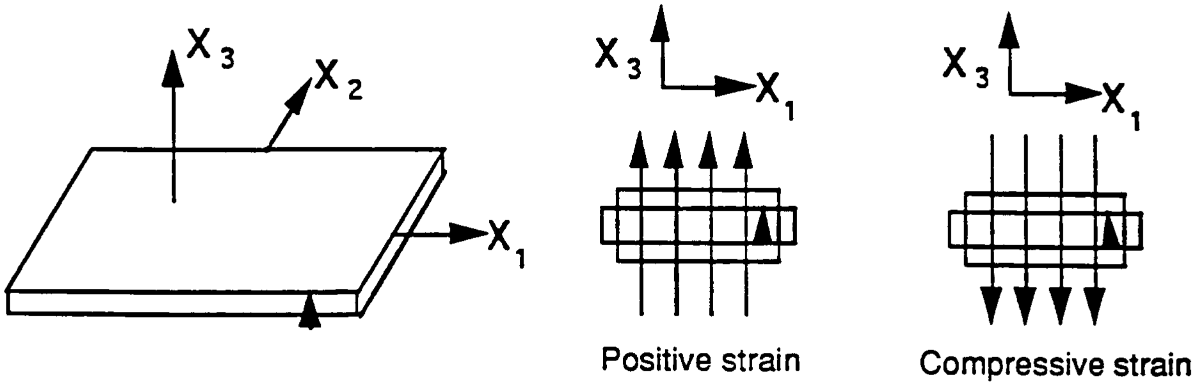
1. DARPA Briefing. "Smart Materials, Devices, and Structures," Feb. 21, 1990.
2. The Concept of Intelligent Materials and the Guidelines on R & D Promotion," Japan Science and Technology Agency, Nov. 30, 1989
3. Advanced Composites with Embedded Sensors and Actuators (ACESA)," Final Report for Period 28 Sept. 1988 - 1 March 1990, R. Iregami, D. G. Wilson and J. H. Laarso, Beoing Aerospace and Electronics Division, Aerospace Systems Technology Organization, P.O. Box 3999, Seattle, WA 93124, AL-TR-90-022 prepared for Astronautics Laboratory (AFSC), June 1990.

APPENDICES

A SMART ACTUATOR CONCEPTS FROM THE ACESA PROGRAM

Concept of operation and evaluation of four smart actuator concepts from the ACESA program (Ref 3):

• Concept of Operation



Polarization direction

Applied Field

- When a field is applied parallel to X^3 direction a positive strain S^3 results
- An opposite field of the same magnitude gives a compressive strain S^3
- d_{31} coefficient characterizes strain perpendicular to poling direction X_1 and X_2 directions) due to an electrical field aligned with poling (X_3) direction. Usually considered a secondary, poisson-like effect resulting from strain due to D_{33} . $S_1 = d_{31} E_3$

• Evaluation

- Stroke limited to maximum of 300 m strain
- Demonstrated embedability in Gr/Ep composites
- Very high bandwidth (greater than 20,000 Hz)
- Ceramic material-very fragile
- Requires very high drive voltages (200-400 volts)
- MIT has demonstrated control of composite beam with embedded piezoelectric ceramic actuators

Figure A-1: Piezoelectric ceramic actuators (from Ref. 3).

- Concept of Operation
  - Magnetostrictive materials:

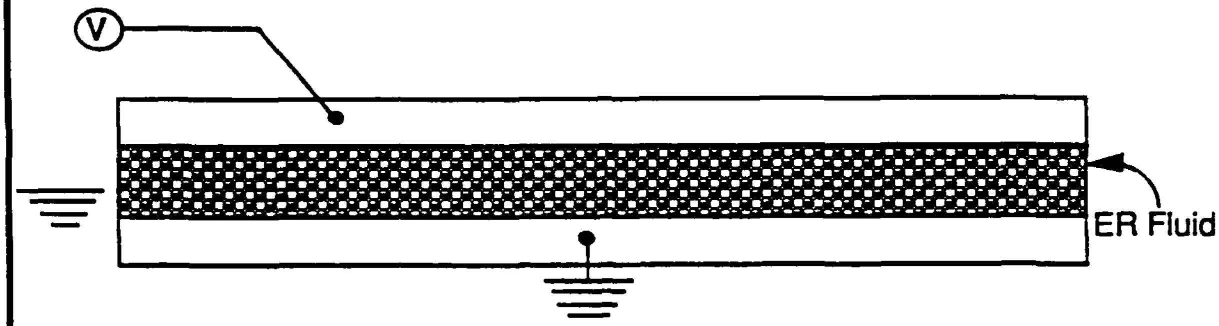
    - A magnetic field is applied to an anisotropic material with randomly distributed domains. The domains will rotate to align with the magnetic field. This causes internal strains in the material which result in a positive expansion of the material in the direction of the magnetic field.

  - Electrostrictive materials:

    - Electrostrive materials self-polarize. Applying a field of these electrostrictive materials begins the process of aligning the randomly oriented electric domains. As the domains align, the material elongates.

      - Magnetostrictive material offer no advantage over electrostrictive materials due to overhead
      - Electrostrictive stroke peak to peak 2000m strain Piezoelectric stroke 300m strain
      - Electrostrictive stroke highly nonlinear at high ends requiring biasing resulting in similar strain range to piezoelectric
      - Some technology development required
      - Neither magnetostrictive nor electrostrictive materials offer any advantages over piezoelectric ceramics

Figure A-2: Magnetostrictive and electrostrictive actuators (from Ref. 3).



- Concept of Operation

  - Changes in electrical field imposed upon the fluid can alter the yield strength of the fluids. By introducing fluid in voids in a composite structure the stiffness and damping characteristics of the composite structure can be changed

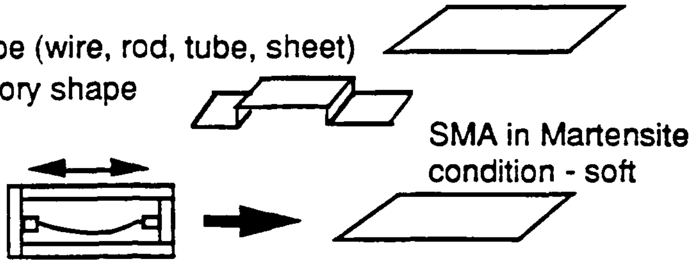
- Evaluation

  - Creates large voids in composite material

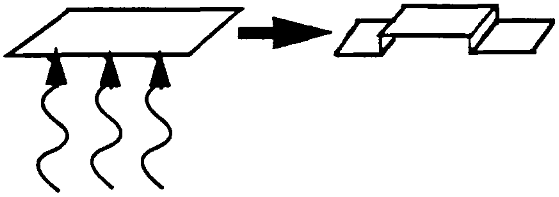
  - Extensive technology development required

Figure A-3: Electro-rheological fluid actuator (from Ref. 3).

- Concept of Operation
  - Produce SMA in basic shape (wire, rod, tube, sheet)
  - Form into the desired memory shape
  - Clamp into fixture
  - Heat treat (anneal)
  - Strain to desired shape



  - Add heat



  - Remove heat and strain to repeat cycle
  - Evaluation
    - Results of thermal analysis for NiTiNOL wire embedded in Gr/Ep
      - Rise times are limited by the circuits ability to supply power and overcome induciton effects
      - Cooling times are limited by the material surrounding the NiTiNOL
      - Cooling will be needed to maintain acceptable temperatures for fast cycling and long soaks
    - Large force capability with lightweight
    - Simple electronics

Figure A-4: NiTiNOL shape memory alloy (SMA) actuators (see Ref. 4).

B EVALUATION OF POTENTIAL FOR POLYMER RESINS AS EMBEDDING MATERIALS FOR SMART SENSOR/ACTUATOR SYSTEMS

- Typical Systems: Gr/Ep, Gr/BMI. Gr/PI
  - Advantages:
    - Mature materials and processes
    - Large experimental base
    - Tailorable CTE
    - Documented physical and mechanical properties
  - Disadvantages:
    - AO, UV, and radiation protection required
    - Outgassing, and moisture absorption controlled with coatings
    - Hostile threat vulnerability
    - Low processing temperatures (250° - 650° F)

S/A embedding potential:

- **Processing temperatures only preclude embedding piezoelectric films**
- **Embedding fiber optics and Nitinol already demonstrated**
- **Hand layup, tube rolling, filament winding easily allows embedding**

Figure B-1: Evaluation of Thermoset Composites (Ref.3)

- Typical Systems: Gr/PEEK, Gr/PPS
  - Advantages:
    - Potential for low-cost fabrication
    - Better toughness than thermosets
    - Potential for simplified
    - Versatility in processing
    - Low out-gassing
  - Disadvantages:
    - Up-front component development costs can be high
    - Lack of experience base in processing
    - Property variability due to processing
    - Difficult to adhesively bond

S/A embedding potential:

- **Processing temperatures exceed fiber optic coating limits**
- **Thermoforming, roll-forming, filament winding still in development**
- **Hand layup, tube rolling, filament winding easily allows embedding**

Figure B-2: Evaluation of Thermoset Composites (Ref.3)

C EXISTING SMART MATERIALS/STRUCTURES PROGRAMS

WHERE	WHO	WHAT
1. AFSC	C. Browning	Active Structural Control
2. A. R. O.	A. Crowson, R. Ghirardelli	Smart Structures
3. Bertin et Cie (France)	Pierre Sansanetti	Smart Structures
4. Boeing Co.	K. Talat	FOS; Smart Skins
5. Caltech	J. Brady	ER Fluid Research
6. Canadian Marconi	Z. J. Lu	FOS for Strain
7. Catholic Univ.	A Bax *et al*	SMA Actuators
8. Cranfield Inst. Tech.	H. Block	ER Fluid Research
9. Duke Univ.	S. K. Das *et al*	Adaptive Structures (Space)
10. E.R. Fluids Devel. Ltd.	J. Stangroom	ER Fluid Research
11. Fla. Inst. Tech.	P. G. Grossman *et al*	Smart Struc., FOS
12. Ga Tech	Hanagud	Piezoceramics, PVDF
13. Lord Corp.	Cary N. C. Duclos	Smart Materials
14. MDAC El. Sys. Div.	Eric Uda	Smart Materials
15. M.I.T.	Crawley, Anderson	Piezo-Ceramic Actuation
16. MSU	M. V. Ghandi	E. R. Fluids
17. NAWC	P. A. Raiti	Smart Structures Skins
18. NASA/Langley	R. S. Rogowsky	Active Control of Space Structures
19. NRL	B. B. Rath	Self Assembly; Smart Mat'ls
20. NRL Adv. F. O. Res. GP.	C. R. Crowe	Fiber Optic Systems
21. N. Car. State U.	Y. Choi et al	ER Fluids for
	Vibration Control	
22. Penn State	Newnham, Cross	Smart Ceramics
23. Simmonds Precision	W. Stillman	Active Control
24. Stanford Univ.	A. Gast (CHE)	ER Fluid Research
25. TRW Space Tech Gp.		Integ. Space Structures
26. Wayne State	Rivin	Passive Self-Adaptive Structures
27. Wright Aero Labs	Stevens, Ghirardi	Health Monitoring,

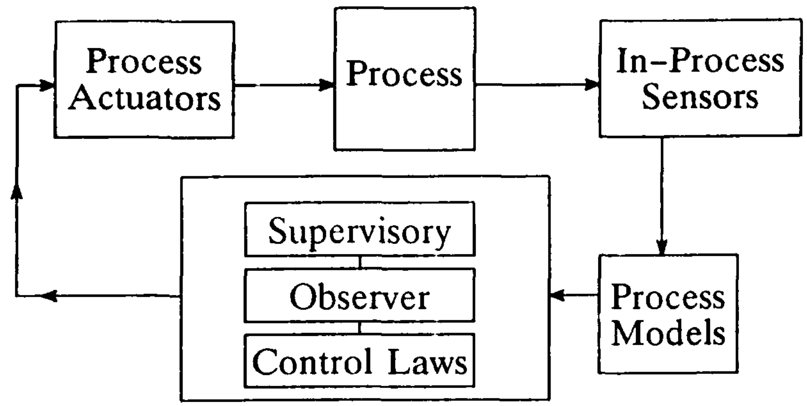
		Structural Integrity.
28. U. Ariz.	P. Calvert	Polymer Fiber Composites
29. U. Fla Gainesville	Zimmerman	Vibration Control of Structures
30. Univ of Quebec/Hull	W. J. Bock	FOS for Strain
31. U. Illinois	C. Zukoski	ER Fluid Research
32. Univ. Maryland	J. S. Sirtis	Smart Structures
33. U. Minn	James	SMA's (Theory)
34. Univ. of Strathclyde	Brian Culshaw	Smart Structures
35. U. Toronto	Measures, Turner, et al	FOS; Strain for Smart Structures
36. UTRC	James Dumphy	Smart Structures
37. U. Utah Ctr. Eng. Design		Micro-Electronic & Mech. Systems
38. Va Tech	Furey	Tribopolymerization
39. Va Tech FEORC	Claus	FOS-Design, Mfr, Test
40. Va. Tech SMSL	Rogers, Ahmad,Robert Shaw	Dynamic Control, SMA's

D FINAL BRIEFING MATERIALS PREPARED FOR ARO

Final briefing materials supplied to Dr. Robert Crowe (ARO). This is an abbreviated version of a briefing package containing over 80 pages of material, which was prepared for ARO by BDM during the program.

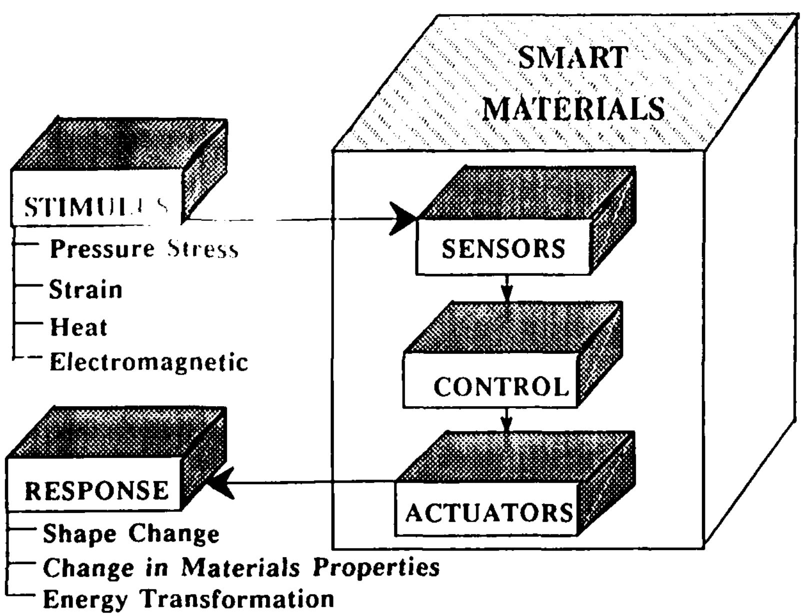
INTEGRATED IPM / SMS PROGRAM

Intelligent Processing of Materials



Heirarchical, Adaptive Controller

Smart Materials & Structures



Technologies Common to IPM & SMS

- Sensing of Material status and response to local environment:
  - during processing (IPM)
  - during service (SMS)
- Models to describe materials / structural response
  - Microstructural evolution and part shaping during processing (IPM)
  - *Mechanical response of material and* adaptive structure to electrical, acoustic thermal or magnetic actuation (SMS)
- Precise, adaptive control for :
  - Active tailoring of process cycle to achieve final microstructure & product goals in material (IPM)
  - Shape and vibration control, pointing precision, health assessment and survivability (SMS)

Both utilize adaptive control methods, neural nets, or rule-based(AI) controllers

INTEGRATED IPM / SMS PROGRAM

PERVASIVE IMPACT

Propulsion	Structural	Acoustic	Infrared	Radar	Optical	Manufacturing
Variable Control Valves	Control Surfaces	Noise/ Vibration Control & Suppresion	3-D Spatial Light Modulator	Electrically Tuned Waveguide	Optical Phase Conjugator	Co-located Sensors/Actuators
Missiles Spacecraft Land-based Engines	Missile Aircraft Structure, Underwater Vehicles	Smart Skins, Machinery Acoustic Suppression	Scene Generation Simulation & Calibration	Electronically Scanned Radar	Solid State Laser Beam Steering, Self Targeting DEW, Optical ATR	Adaptable Tools Vibration & Jitter-Free Processing

RESULTS: Early development & exploitation of these smart materials will result in lighter weight, more manufacturable, and more reliable weapon systems.

INTEGRATED IPM / SMS PROGRAM

Definitions

- **Intelligent Processing of Materials (IPM)**

  -- Active, ADAPTIVE CONTROL of materials processing utilizing IN-PROCESS SENSING of critical microstructural and overall product features as they evolve, during processing, utilizing numerical and heuristic MODELS of the process to MODIFY the process schedule (T, P, flow rates) as required during processing to achieve optimized, reproducible product goals.

- **Smart Materials & Structures (SMS)**

  -- Structural systems based upon materials with the ability to SENSE their own response to environmental and operational stimuli, and to MODIFY that response in such a way as to maintain or optimize structural performance, utilizing embedded sensors and actuators interfaced with closed loop, ADAPTIVE CONTROL systems based upon system response MODELS.

INTEGRATED IPM / SMS PROGRAM

Issues

IPM

- Successfully being applied to individual process steps (HIP, CVD, crystal growth)
- Currently suboptimal for production of materials/structures involving multistep processing
- IPM–based control of multistep processing is a key to integrated IPM/SMS effort

SMS

Sensor & Actuator Materials

- highly sensitive to processing (large scatter in properties) – requires IPM
- small (or nonexistent) supplier base
- scattered, small database on acousto–, electro–, opto–, and magneto–mechanical behavior

Incorporation of Sensors, Actuators, and Controls into Structures

- design concepts for systems with inherently nonlinear response is immature
- micromechanical behavior and stability of smart composites largely unknown
- automated production equipment will be required – largely undeveloped

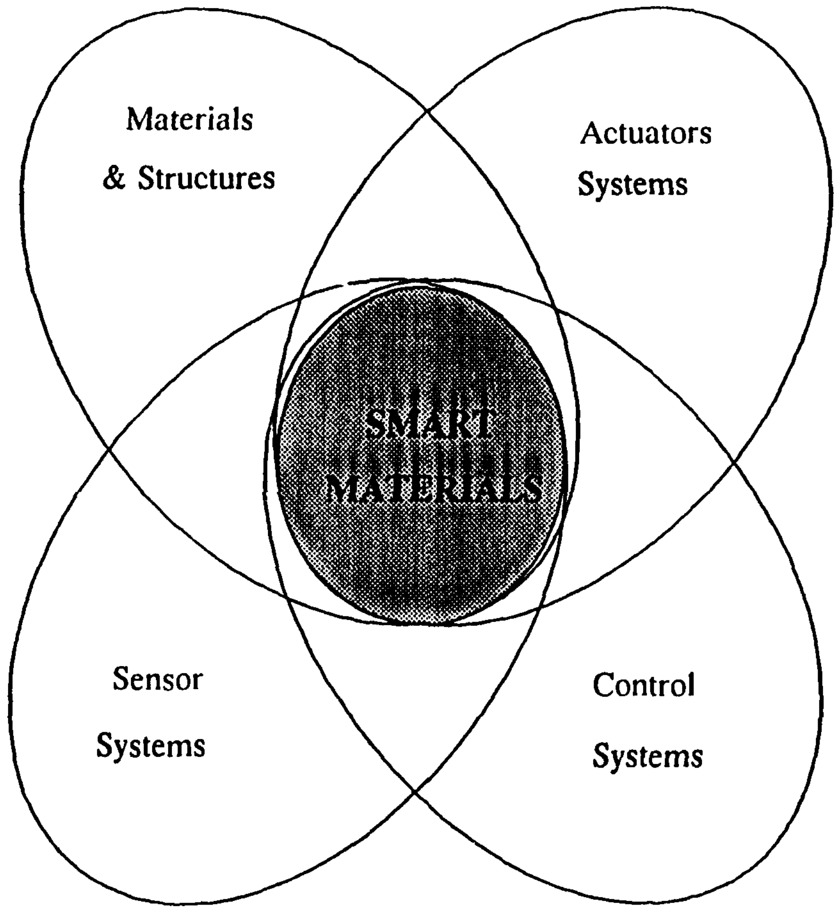
Adaptive control of nonlinear systems

- intense ongoing research on control of robotic and other highly nonlinear systems which should be leveraged

E BRIEFING MATERIALS PREPARED FOR DARPA

Briefing materials supplied to Dr. Ben Wilcox (DARPA) describing how IPM and SMS technologies have synergy for long term advances in Smart Materials system applications.

SMART MATERIALS AND STRUCTURES



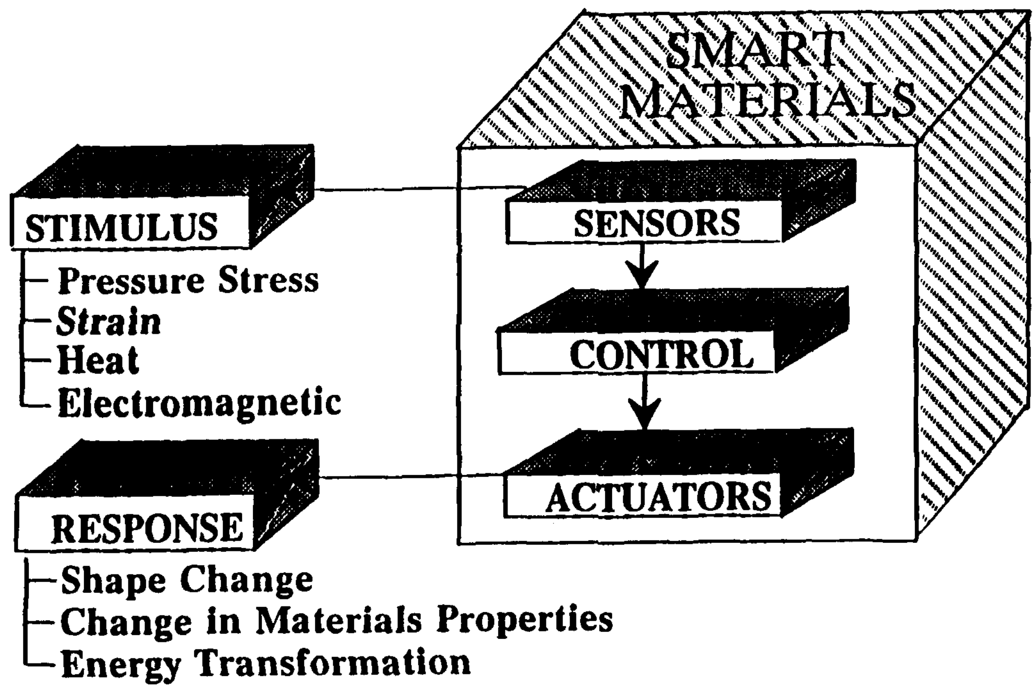
SMART = Fully Integrated { Sensing of Environment, Actuation of Response, With Active Control

SMART MATERIALS AND STRUCTURES

Payoffs

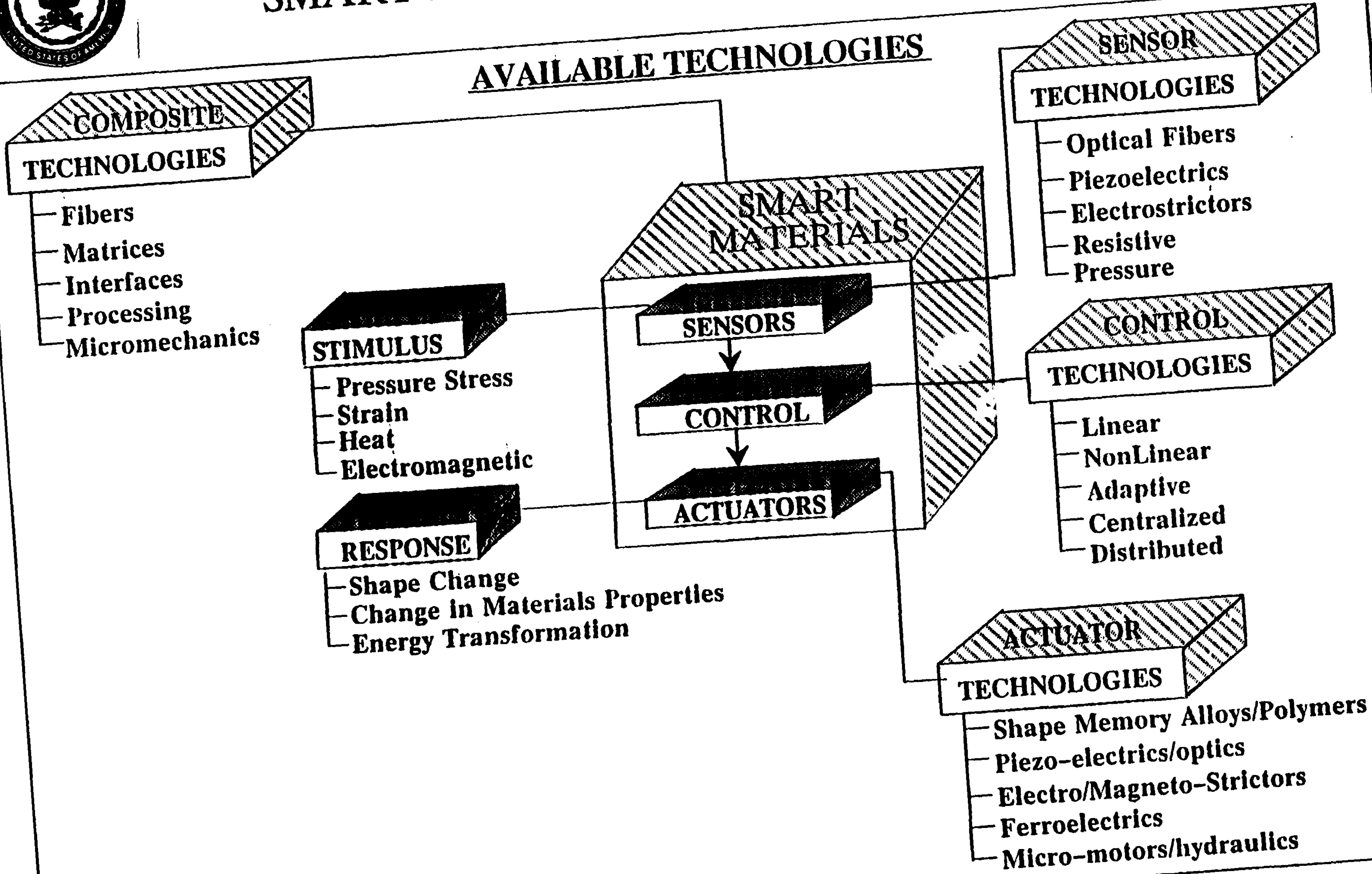
Application	Systems	Payoffs	Mission Benefits
Adaptive Control Surfaces	Aircraft (Wings & Control Surfaces)	2x Increase in Lift-to-Drag (L/D) Ratio	30% Greater Payload 50% Longer Range 30% Increase in Maneuverability
Active Acoustic Coatings for Signature Suppression (Broad Band)	Submarines (Coatings)	60 dB Noise Suppression 100x Reduction in Settling Time	Active Stealth 2x Listening Range
Vibration Suppression & Twist Control	Helicopters (Blades)	Active Blade Trimming & Balancing 3% Gross Wt. Reduction	15% Increased Readiness Increased Speed – 160–200 Knots Increased Agility
Active Structural Tuning & Damping	Precision Space Structures	1 μm Adjustment over 25 m	Pointing Accuracy

SMART MATERIALS AND STRUCTURES



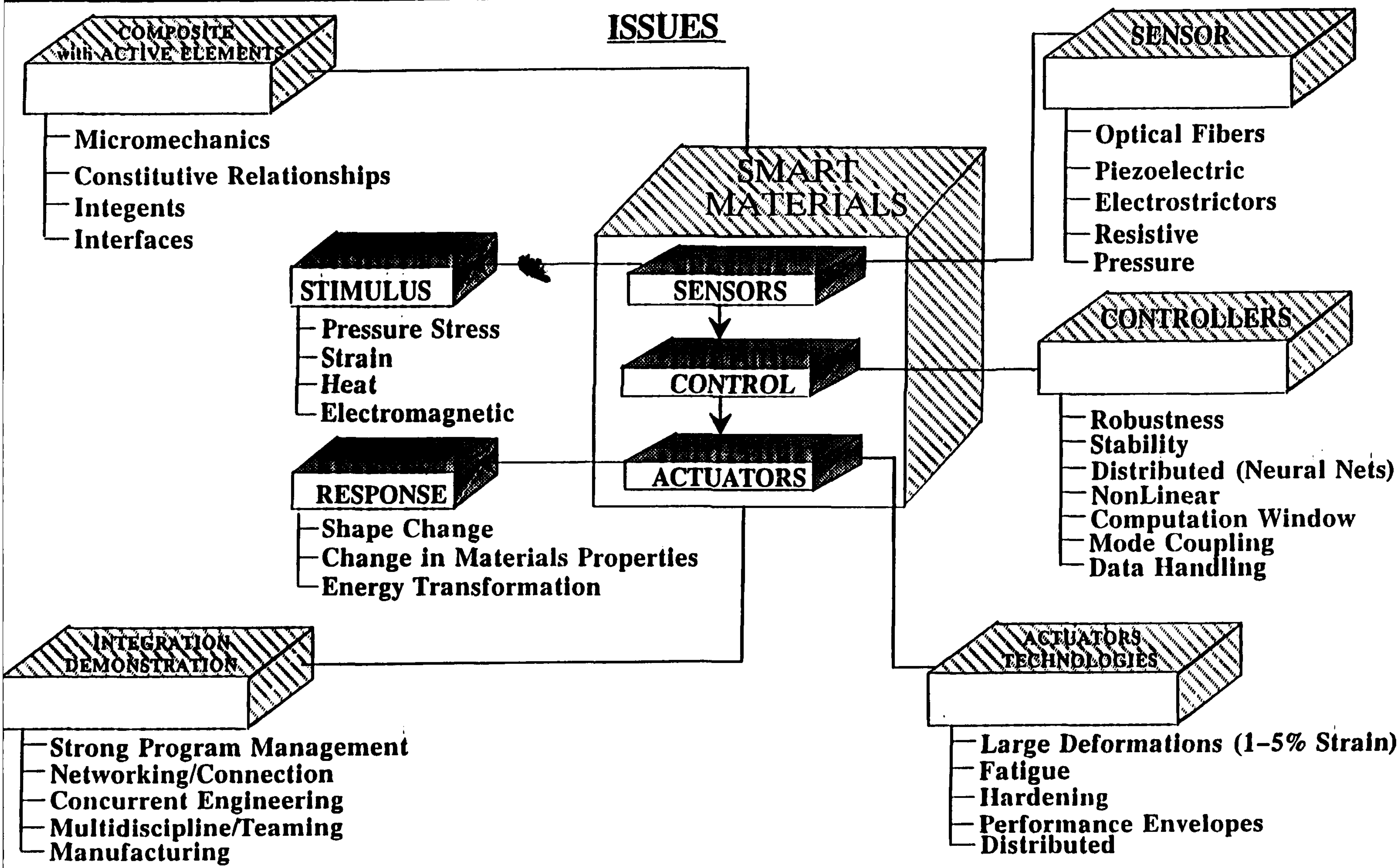
SMART MATERIALS AND STRUCTURES

AVAILABLE TECHNOLOGIES



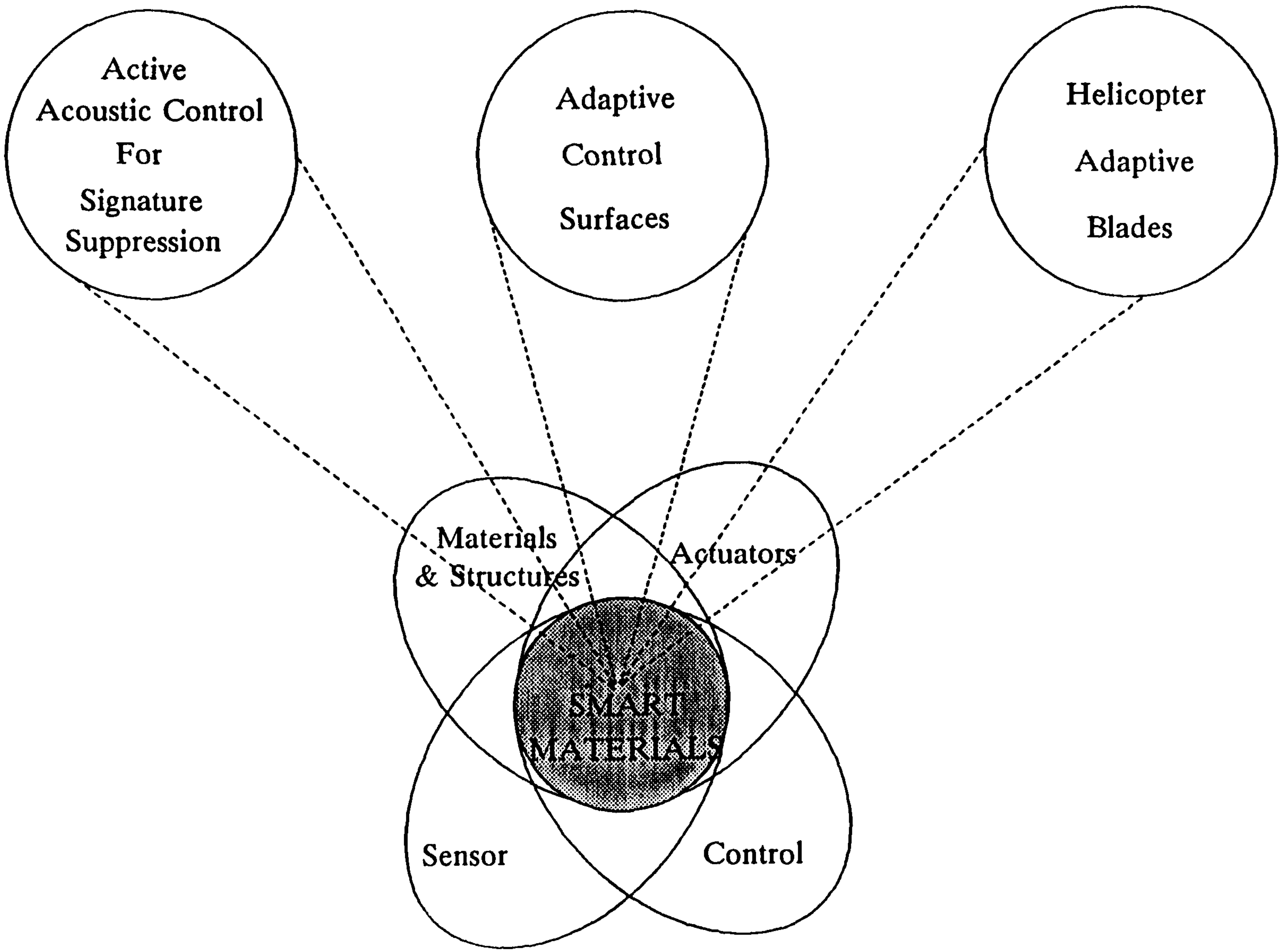
SMART MATERIALS AND STRUCTURES

ISSUES



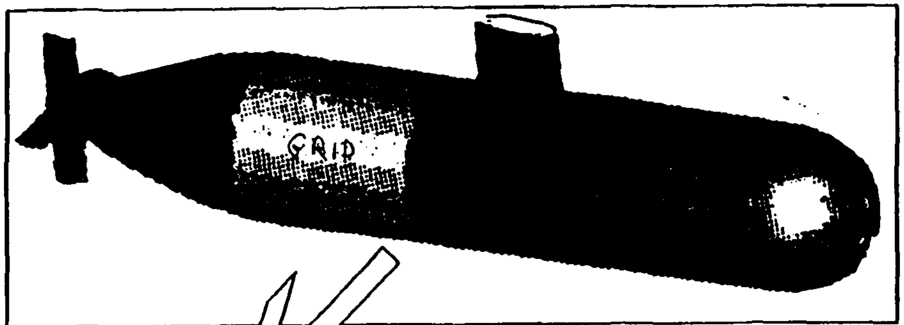
SMART MATERIALS AND STRUCTURES

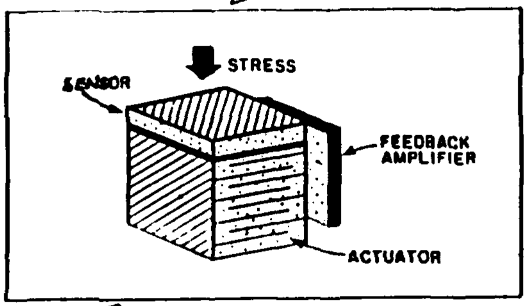
Demonstration Candidates

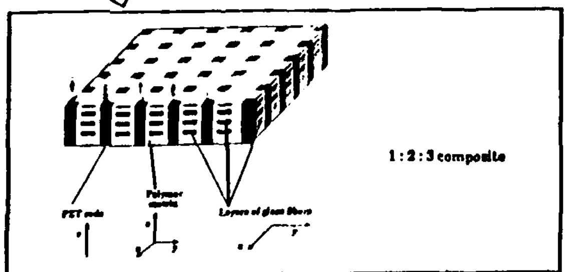


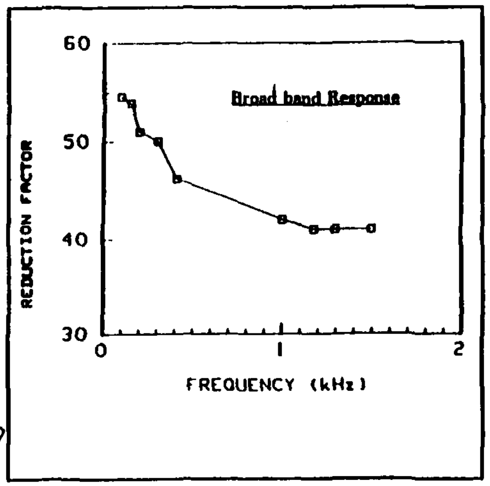
SMART MATERIALS AND STRUCTURES

Active Acoustic Coatings for Signature Suppression







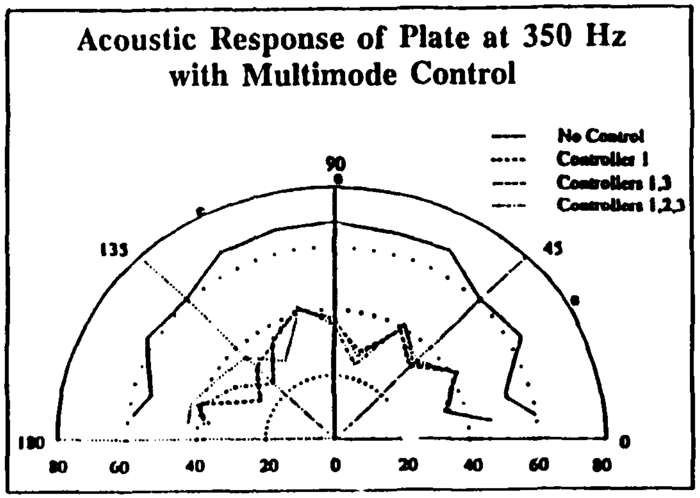


Requirements:

- Small Movements (μ m's)
- Response Times
  - Dynamic (KHz, localized control)
  - Static (long–wavelength, distributed control)

Payoff: Active Acoustic Stealth

- Up to 60 dB Reduction in Radiated Noise
- 100x Increase in Settling Times

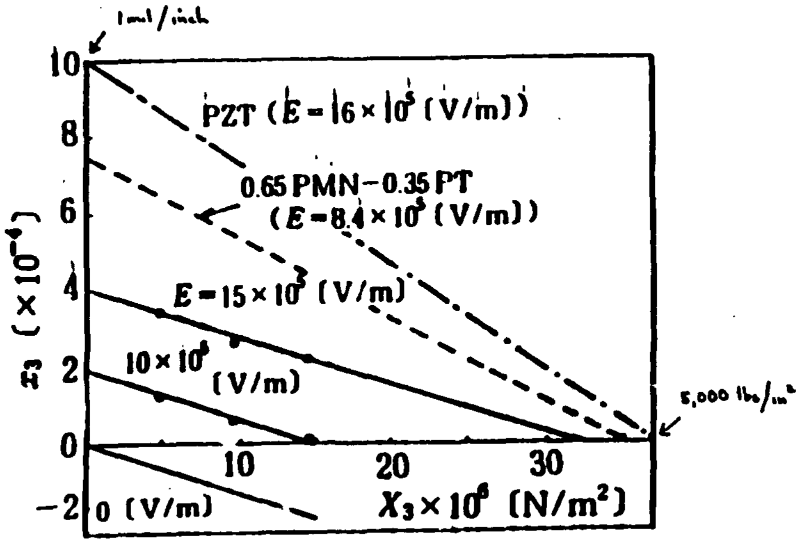


SMART MATERIALS AND STRUCTURES

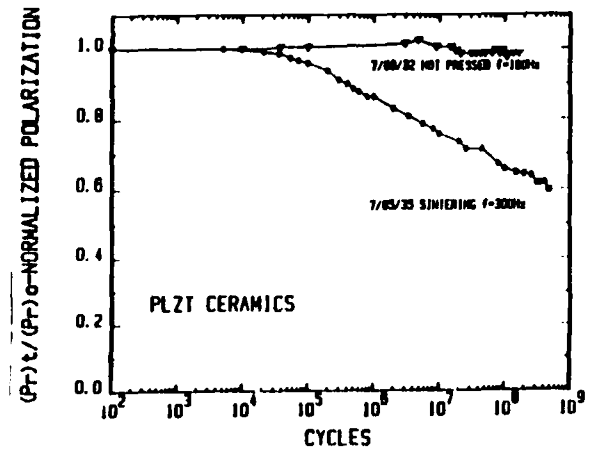
Active Acoustic Coatings for Signature Suppression

ISSUES

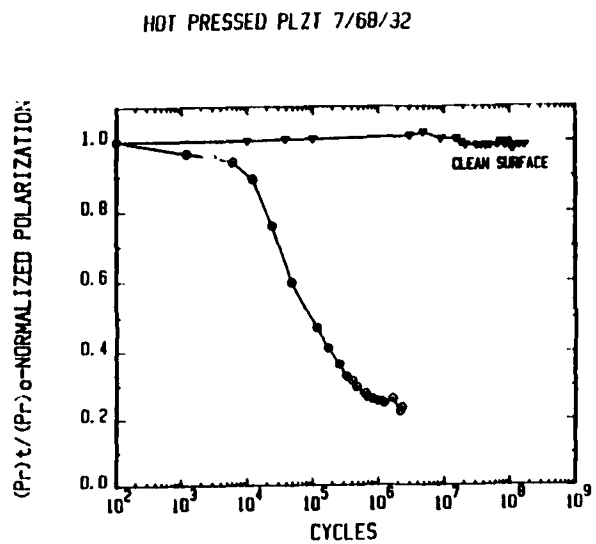
Actuation



Processing



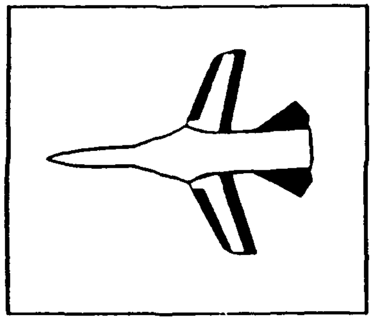
Response Degradation



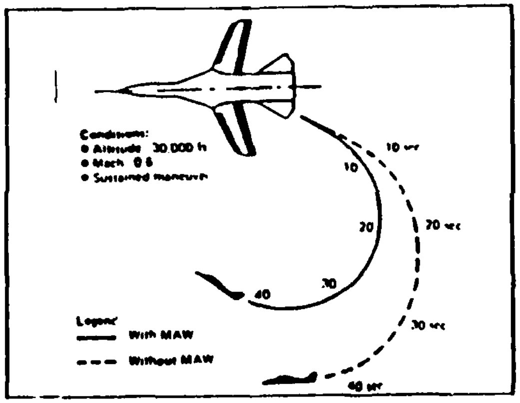
Design/Manufacturing

- Design Rules Incorporating Embedded Sensors, Actuators
- Conventional Processing Methods (e.g., tape casting)

SMART MATERIALS AND STRUCTURES



Adaptive Control Surface



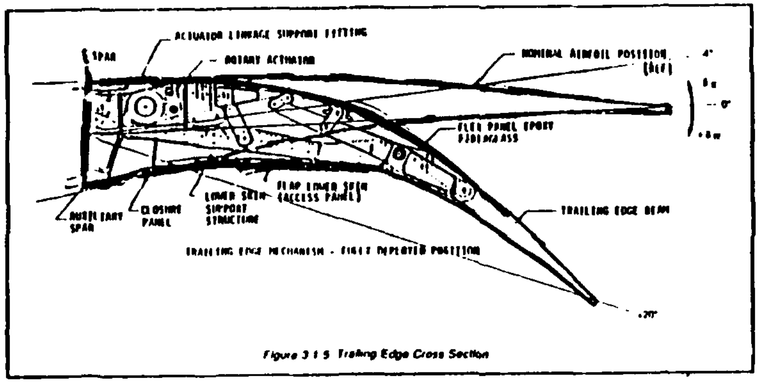
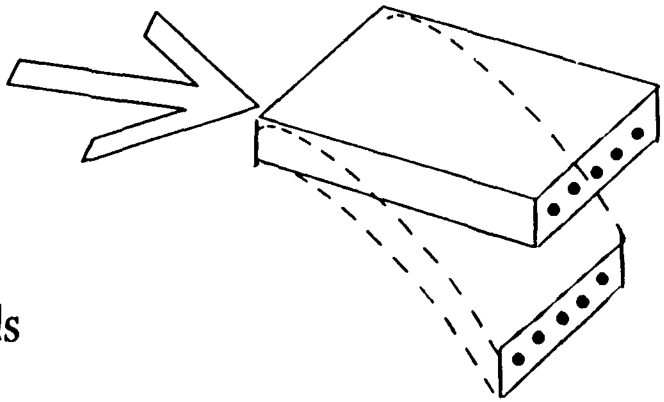


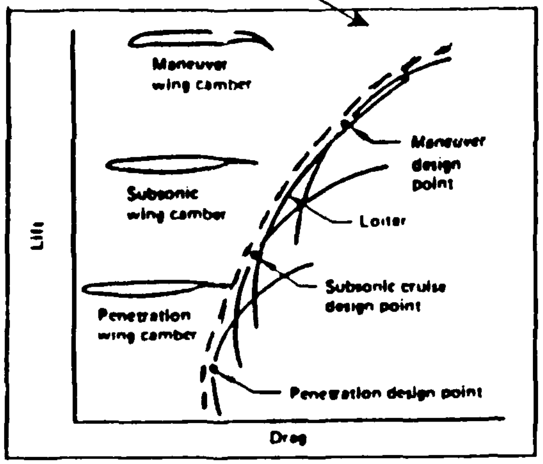
Figure 3.1.5 Trailing Edge Cross Section

Eliminates
Hydraulics

Adapt'ive
Panel



Variable Camber Envelope



PAYOFFS

- 30% Higher Payloads
- 50% Longer Range
- 30% Increased Maneuver

SMART MATERIALS AND STRUCTURES

Adaptive Control Surface

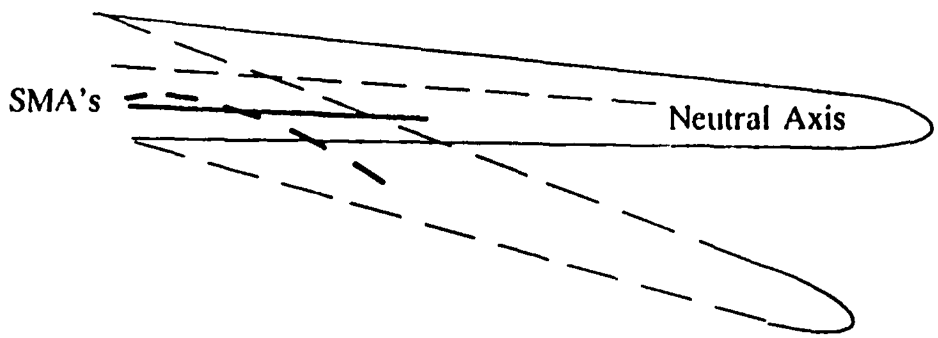
ISSUES

Large Scale Deflection

- Structural Integrity with Large Deflection Capability (1 – 5% Strain)

Fatigue Failure

- Performance Degradation with Flaws
- Failure Mode Modeling

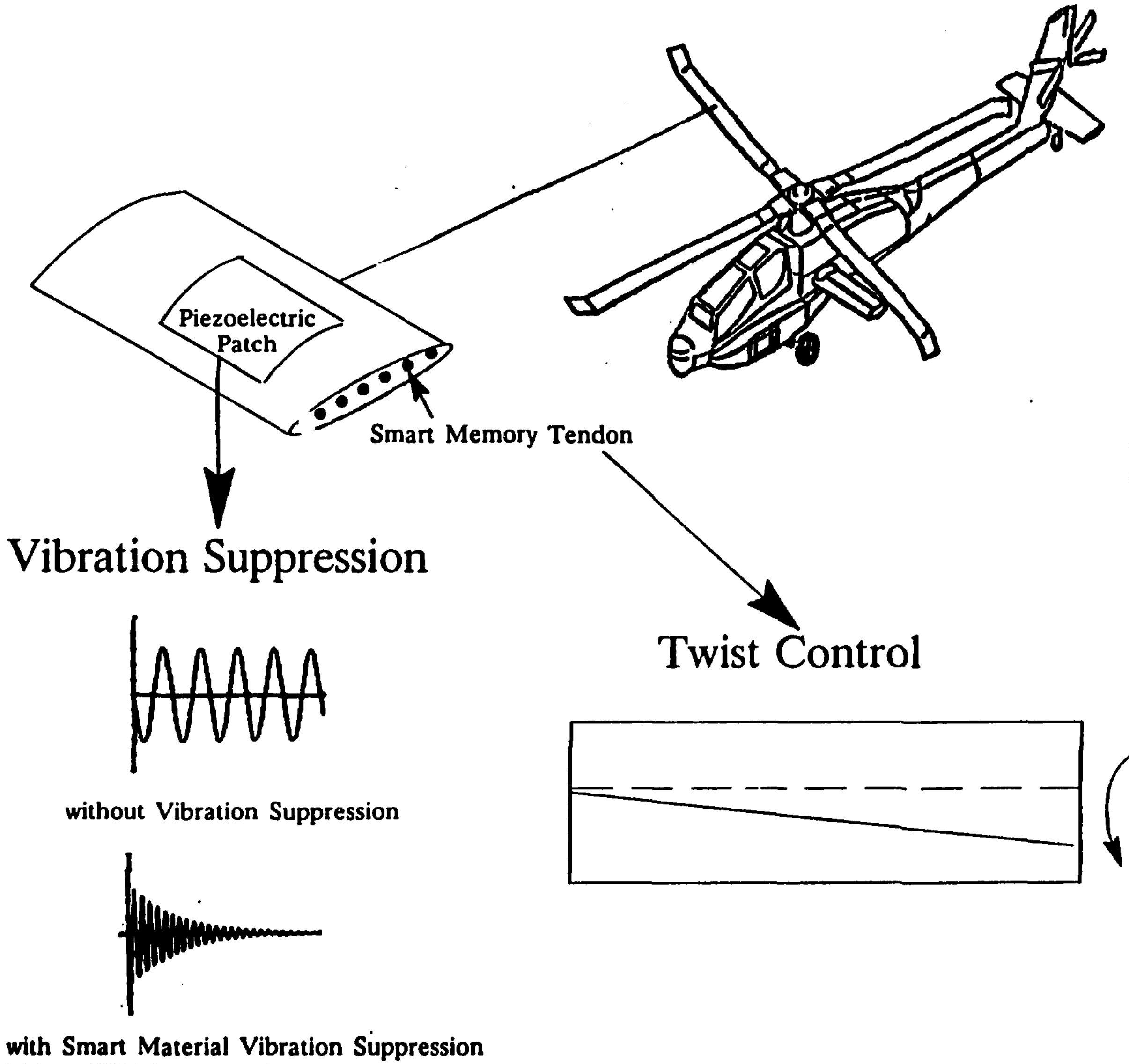


Actuation – SMA's

- Strain as a Function of Transition Temperature
- Operating vs Transition Temperature (Power requirements)

SMART MATERIALS AND STRUCTURES

Helicopter Blade Vibration Suppression & Twist Control



Requirements:

Vibration Suppression:

Response: 1–100 Hz

Displacement: μ

Twist Control: (Blade Trimming)

Response: Static to 12 Hz

Displacement: mm

Payoffs

Increased Speed (from 160 to 200 Knots)

Increased Readiness at least 15%

Increased Range

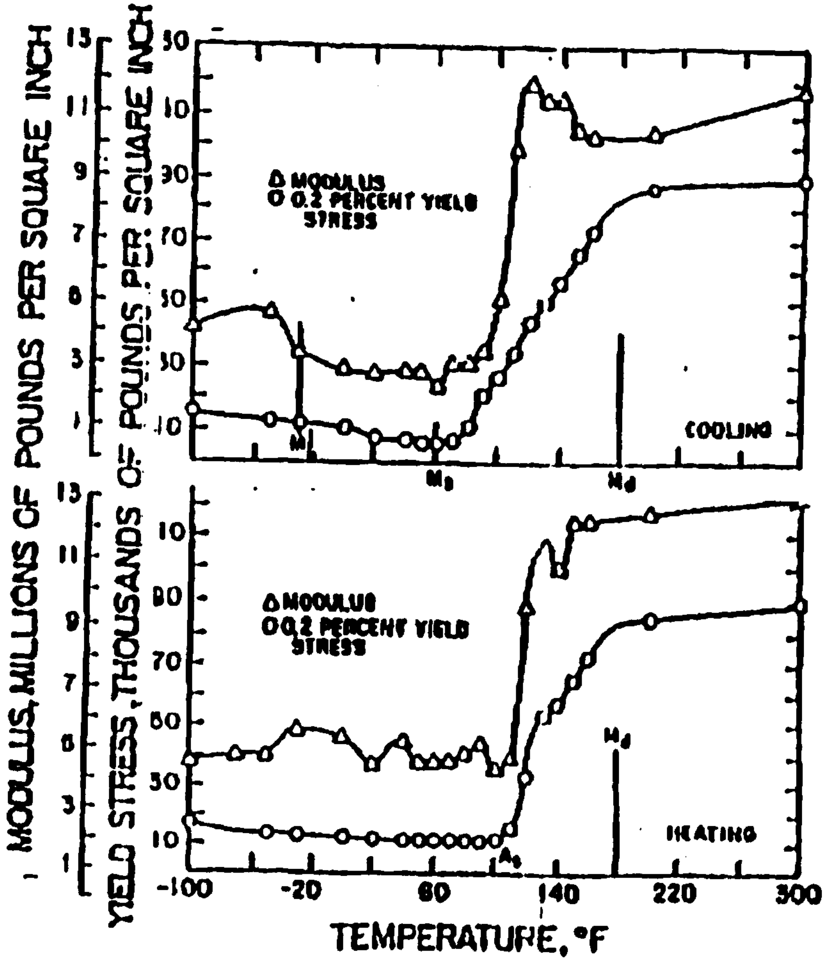
Increase Maneuverability

SMART MATERIALS AND STRUCTURES

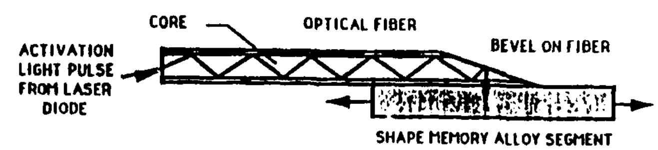
Helicopter Blade Vibration Suppression & Twist Control

ISSUES

Actuation



Distributed Heating



OPTICAL ACTIVATION OF SHAPE MEMORY ALLOY

Control Structure

- Robustness and Stability
- Distributed Control for Vibration Suppression
- Centralized Control for Blade Twist

F RELATED WORK PREPARED BY BDM PERSONNEL

During the program, related activities were pursued by BDM personnel at no cost to the program.

Dr. Norman M. Wereley prepared a paper on a prototype micro-gravity vibration isolation mount using PVDF film as actuators. This paper was presented at the International Symposium and Exhibition on Active Materials and Adaptive Structures in Alexandria, Virginia, on 4-8 November 1991. The PVDF film is a polymer exhibiting piezo-electric properties. The paper is attached.

MICROGRAVITY ISOLATION FOR SPACECRAFT PAYLOAD [1]

M. Mercadal, [2] C.A. Blaurock, [3] A.H. von Flotow, [4] and N.M. Wereley [5]
Department of Aeronautics and Astronautics: Massachusetts Institute of Technology,
Rm 37-335: Cambridge, MA 02139

ABSTRACT: A laboratory prototype of a six axis microgravity isolation mount is presented. to provide a microgravity or micro-GEE ($9.81 \times 10^{-6} m/s^2$) vibration payload environment on board a milli-GEE ($9.81 \times 10^{-3} m/s^2$) spacecraft. The design can be adapted for NASA space shuttle or Space Station Freedom missions. The mount accomodates data. power. and cooling umbilicals of limited stiffness. Actuators are currently implemented using piezoelectric film.

1. MICROGRAVITY ISOLATION REQUIREMENTS

Mission specialist Bonnie Dunbar. on mission STS 32. measured acceleration levels above 10 mGEE ($9.81 \times 10^{-2} m/s^2$), especially when the crew members perform treadmill exercise. Figure 1 from [1] shows a typical vibration time history measured in the orbiter cabin. Preventive actions. such as shutting off unnecessary motors or restricting crew physical exercise. can reduce vibration during vibration sensitive experiments. but is impractical for extended periods.

Current NASA/ESA specifications consider harmonic disturbances only. More stringent requirements on the combined effects of broad-band GEE-jitter (crew motion. control thruster firings. sound etc.) and narrowband disturbances (antennae motion. rotating machinery. breathing etc.) need to be developed [2]. The single harmonic concept puts upperbounds on known narrowband disturbances and produces a curve of environmental disturbances as shown in Figure 2a [3]. The desired curve is Figure 2b. a combination of [4] and NASA specifications [2] from [3]. The two curves clearly emphasize the need for isolation.

2. MIT SIX AXIS ISOLATION MOUNT

The vibration isolation concept involves softly mounting an inner box to the shuttle. so that vibrations of an outer container are not transmitted to the inner box. A 2 cm gap is provided between the inner box and the outer box. following recommendations by [3]. A mount travel of 1 cm is accomodated before the mount "bottoms out" on rubber bumpers. This is four times greater than the travel implied by the transmissibility specification of Figure 2. A 1 cm sinusoid at 0.01 Hz produces 4 micro-GEE of acceleration.

The soft mounts are implemented using piezo-electric (PVDF) film. The film. in appropriate shape configurations. behaves like a soft spring to mechanically isolate the inner box from the outer box. Second. the film deforms when voltage is applied. and can be used as an actuator. Active feedback control is used to increase damping, and to further soften the mount. Combined

[1] Presented at the *International Symposium and Exhibition on Active Materials and Adaptive Structures*: Alexandria. Virginia: November 4-8. 1991. Substantially revised version of a paper presented at the 42nd Congress of the International Astronautical Federation: Montreal. PQ, Canada: October 7-11. 1991. This research was supported by the McDonnell-Douglas Space Systems Company with technical monitors Y.T. Chung and J.J. Tracy.

[2] *Visiting Scientist.* Currently: Compagnie Dassault. Paris. France.

[3] *Research Engineer*

[4] *Associate Professor*

[5] *Research Scientist.* Currently: Staff Member. Control and Sensor Technology, BDM International Inc., 4001 N. Fairfax Dr.. Suite 750. Arlington, VA 22203

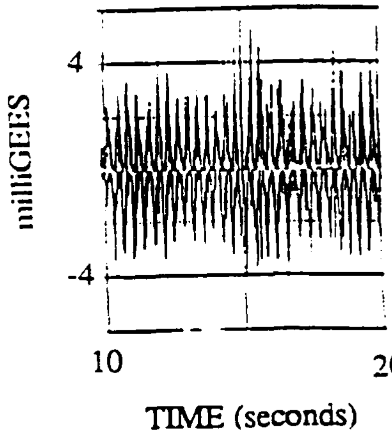


Figure 1: Shuttle middeck vibration time history during STS 32 flight

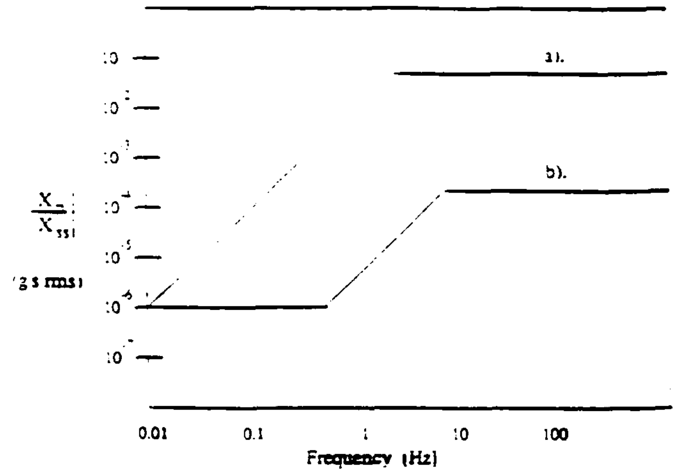


Figure 2: Single harmonic vibration requirements by Jones *et al*

active and passive action limits the need for active control: open loop performance of the mount is quite good, even though it falls short of the specifications in Figure 2.

Actuators were mounted so that three translations and three rotations of the inner box can be equally well controlled. Coupling between the six degrees of freedom is minimized to simplify control application. Each actuator is paired with an accelerometer. Decoupling the dynamics enables the entire system to be identified on the ground with partial tests only. This reduces the requirement for on-orbit identification. The control system can also be validated on the ground before launch.

From a survey of proposed microgravity experiments, flow of information, power, coolant, and vacuum must occur between the payload and spacecraft. Utility umbilicals will add stiffness to the system which is undesirable, so that umbilical stiffness should be minimized in order to achieve as soft a passive mount as possible, reducing the need for feedback control.

3. EXPERIMENTAL APPARATUS

The isolation system has been sized so that the isolated payload fits inside two standard NASA Space Shuttle middeck lockers. Wyle Laboratories [5], has developed the Universal Small Experiment Container (USEC) system shown in Figure 3, which fits inside two space shuttle mid-deck lockers and satisfies NASA safety standards for experiments flown on the shuttle. The USEC is proposed since microgravity payloads such as crystal growth or biological experiments require this degree of containment. The isolation system is part of the payload as far as the integration process is viewed by NASA.

The piezo-film actuators were modelled as a displacement source in series with a spring. The primary role of the actuators is to overpower the utility umbilicals and soften the mount. The payload box is nominally still, so that little control effort is used to overpower payload inertia. The utility umbilicals were lumped together and given a stiffness equivalent for all axes. Thus, the force on the actuator is the umbilical stiffness times the box relative motion. The derivation of actuator stiffness and free deflection is detailed in [6]. The actuators, as configured in Figure 4, actuate all six axes, and each kinematically actuates only one degree of translation and rotation. Rear actuators were doubled up to maintain equal control authority in the X axis. The actuators were nominally flat to maximize payload volume. The total mount stiffness measured was 5 N/m per axis. The mount was designed to handle an umbilical with 20 N/m stiffness. The design and fabrication of the actuators is detailed in [6].

The experiment focused on actuator validation, so that a mock-up of the locker and payload

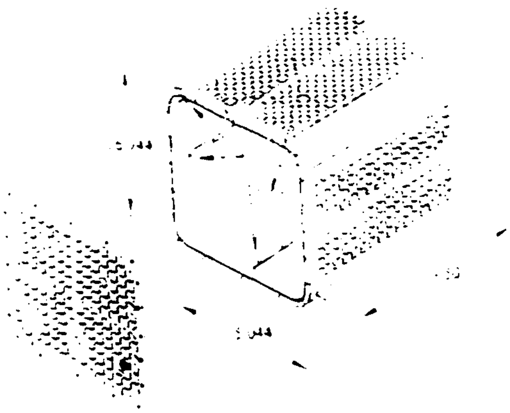


Figure 3: The Wyle Laboratories USEC containment box satisfies NASA's containment specifications for the shuttle middeck.

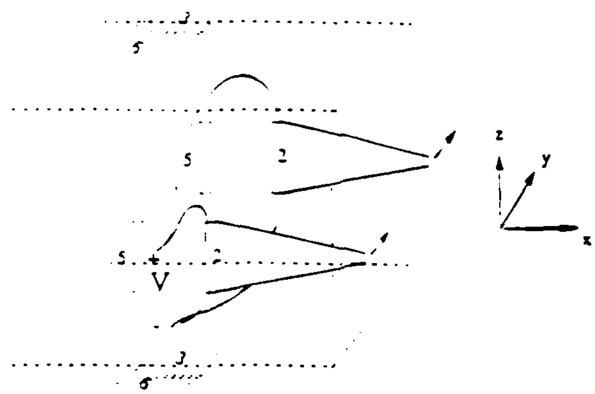


Figure 4: Actuators are configured such that two push at each location.

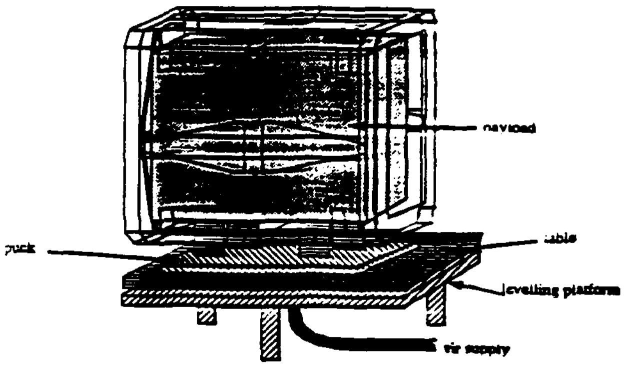


Figure 5: Experiment hardware.

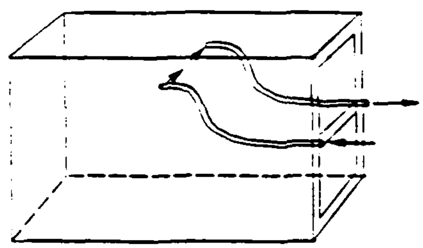


Figure 6: Placement of coolant umbilical.

was fabricated with representative dimensions and properties. During proof–of–concept, easy access to system components was required. As shown in Figure 5. the front panel was open to permit payload removal. Bumpers prevented damage to the actuators due to excessive payload motion. Actuator attachment locations were provided on all four longerons. and at the rear vertical bar. The actuator attachment hardware allowed nominal centering of payload. The payload rested on an air table with minimial damping, to permit free movement in the horizontal plane.

Actuator power was supplied by three Kepco BOP 1000M high voltage ampiifiers. for which their maximum current output of 40 milliamps proved to be barely sufficient. Three shakers were used to excite the system. one for axial motion. and two at the side of the locker. to allow 2 transiations. and rotation around the vertical axis. The shaker heads were connected to the core of an LVDT linear position sensor. so that transmissibility from locker motion to payload acceleration could be measured directly.

Sundstrand QA-1400 accelerometers were mounted on an adjustable platform that could be tilted to remove the accelerometer's DC bias by cancelling it with a component of gravity. Looped computer ribbon cable was used for the sensor umbilical. The modes of the experiment

with the ribbon cable in place were compared to the dynamics of the payload with accelerometer connections of very thin magnet wire. Utility umbilicals consisting of accelerometer cabling and a simulated coolant hose, sufficient for 1 KW of cooling with less than 50 degrees Celsius temperature increase, were implemented. The system ID places constraints on the umbilical locations, since some coupling terms in the stiffness matrix cannot be identified [6]. The umbilicals were attached symmetrically about the payload center of mass, as shown in Figure 6 to minimize unidentified coupling. Each coolant hose was looped, so that the hose was never stretched. The stiffness was found to be 8.2 N/m in the X direction, and negligible in the Y axis.

4. SYSTEM IDENTIFICATION

Ref. [6] details an analytical model of the system based on system geometry, its mass and inertia characteristics, the umbilical and actuator stiffnesses. This model is valid at low frequency (below about 10 Hz) where the control system exercises most of its authority.

Mechanical properties, such as mass, inertia, or stiffness, can be measured, or computed from detailed engineering drawings. However, system identification of the physical system should prove convenient information suitable control design. The six axis mount could be identified on-orbit. However, system ID would be time consuming due to low natural frequencies of the mount, with computational requirements far exceeding those for closed loop control. Thus, we propose six axis ground-based system ID, using three sets of three axis system identification tests. A single three axis test consists of resting one side of the inner box on an air table while suspending the outer box appropriately. This setup allows two translations and one rotation, and permits the identification of a projection of the unrestricted six degree of freedom motion. The accuracy and the validity of this strategy depends strongly on the decoupling of the dynamics. After the three 3-axis tests are performed, the identified stiffness matrix, K, is known except for those entries designed to be small, that is, identification cannot determine: helicoidal spring constants where a translation produces a torque in the same axis or torsional spring constants not aligned with one of the geometrical axes. Such springs have however been eliminated by design. Details of the 3-axis system identification is deferred to Appendix 1 of [6].

Single-input multi-output system ID of the three axis testbed was performed using a Tektronix 2630 Fourier analyzer, which computed transfer functions, and coherence functions. An ensemble average of 15 runs takes 39 min 45 sec. A weighted least mean square algorithm was used to determine a state space model [6]. The test was performed on the system equipped with two rubber hoses attached on the Y sides of the inner box to simulate the cooling apparatus. Excellent agreement is obtained for both magnitude and the phase. The resonant frequencies are at 0.124 Hz and 0.181 Hz for the Y and X translational modes (the umbilical separates the frequencies) and at 0.273 Hz for the rotational Z mode. Comparing with a second test performed without umbilical, the umbilical stiffness is estimated at 8.2 N/m, which is within design specifications.

Modal damping was identified to be between 4% and 6%. Also, the damping matrix, C, was not aligned with the stiffness matrix, so that modal decoupling was not completely effective. In Figure 7, the transfer function (magnitude only) of the decoupled plant is plotted. The off-diagonal elements of the transfer function matrix are substantially smaller than those on the main diagonal, but are not negligible.

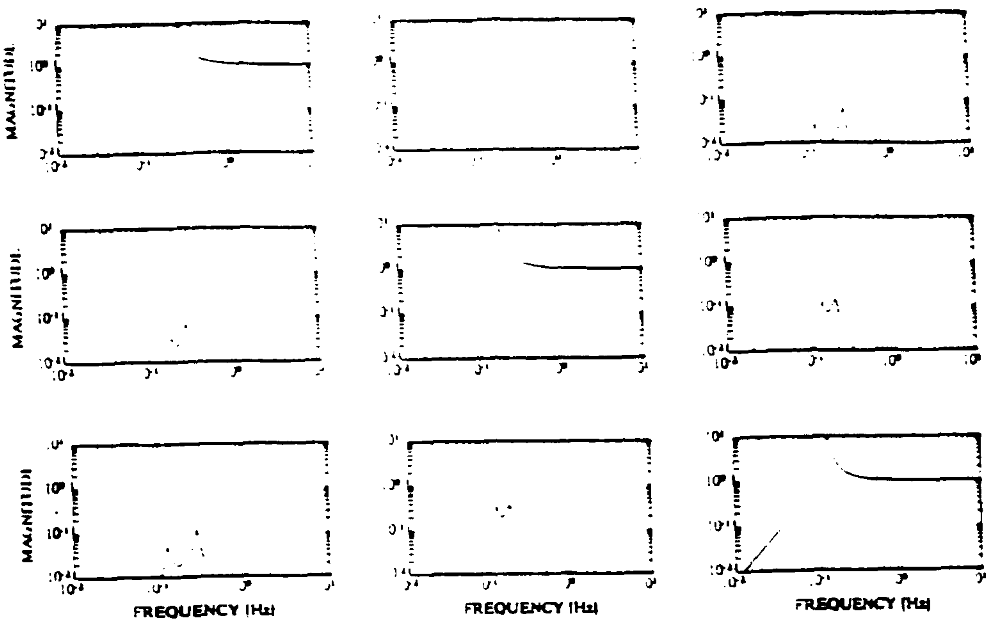


Figure 7: Decoupled identified transfer functions of the 3 axis test with umbilical: magnitude

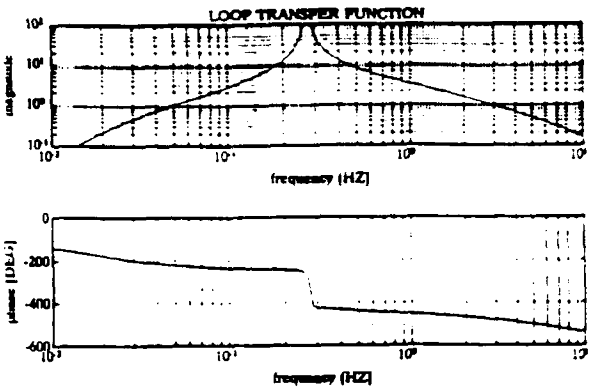
5. CONTROL OBJECTIVES

The control objectives set by the NASA/ESA guidelines, [3], require the closed loop poles of the isolated payload to be at 0.05 Hz (curve a) or 0.01 Hz (curve b), with a damping ratio above 0.707. The control strategy is to combine sensor and actuator signals to modally decouple the system, and close a single input single output (SISO) control loop around each of the 6 decoupled modes. The advantage of the decoupling strategy over purely localized control between collocated sensors and actuators is that *spread in modal frequencies can be equalized* due to the spread in the stiffness matrix. With such a well-conditioned plant, however, six localized feedback loops are still possible, one for each (local) sensor/actuator pair. In order to drive the fastest mode to the required frequency, the localized scheme will require higher gains.

To reduce the natural frequency of the system, modal mass must be increased, or modal stiffness must be decreased. To improve modal damping and phase margins, velocity feedback was implemented. Acceleration feedback was selected for this application, over position feedback, because accelerometers were much less expensive than gap sensors of comparable sensitivity. Gap sensors can be easily accomodated in the current controller framework, and may be implemented in future work.

The design target will be to set the closed loop modal frequencies $\omega_{cl} = 0.01$ Hz (requirement a) or $\omega_{cl} = 0.05$ Hz (requirement b), with damping $\zeta_{cl} = 1$ to eliminate overshoot. However, phase losses from digital controller implementation and anti-aliasing filters will decrease closed loop damping.

The high-pass filter is a two-pole filter with corner frequency at 0.02 Hz. The corner frequency of the high pass filter was selected to prevent saturation of the actuators due to biases and bias drifts present in accelerometers and associated conditioning amplifiers. The filters ensure that modal mass is added only in the frequency range of interest. The high-pass filter adds phase lead and may reduce the amount of damping provided by the feedback loop, especially if the filter frequency is too high. The low-pass filter is a one-pole filter at 0.3 Hz followed by a two-pole filter at 10 Hz. The double pole filter at 10 Hz reduces high frequency accelerometer



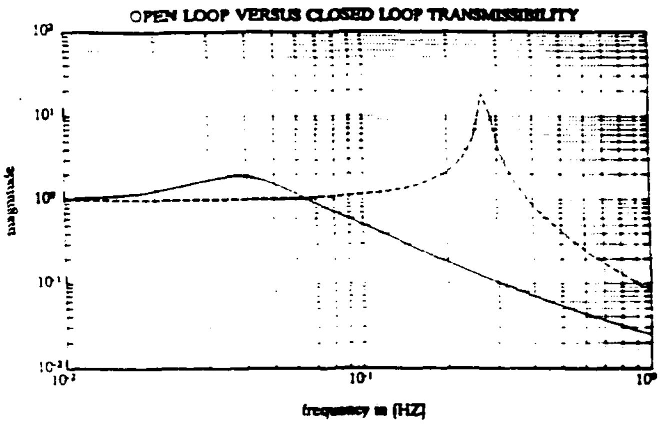


Figure 8: Loop transfer function of Z rotation mode, 0.2726 Hz. with filters

Figure 9: Open versus closed loop transmissibility of Z rotation mode

noise. and serves as anti-aliasing filters. In order to maintain stability. a one pole roll off is needed at cross-over with enough phase lead to prevent instabilities. The corner frequency of 0.3 Hz was selected for that purpose.

The filters have a significant effect on the closed loop dynamics since their corner frequencies are close to the natural frequencies of the system. be it closed or open loop. The high-pass filter reduces the phase lag introduced by the integrator and will therefore reduce the amount of passive damping in the system. However. the 0.3 Hz low-pass filter adds some phase lag and compensates somewhat for the lead. The choice of the m_i and c_i must therefore be iterated until a satisfactory compromise is reached. The closed loop frequencies and damping will be very different from the prediction based only on the second oscillator model for the modes. The target for the closed loop is to set the modes at 0.04 Hz with as much damping as the wash-out filter can allow. The accleration feedback gain. $m_{(.)}$. and the velocity feedback gain. $c_{(.)}$, chosen in the experiment are: X Translation Mode. 0.1807 Hz. $m_x = 4$. $c_x = 4$: Y Translation Mode. 0.1236 Hz. $m_y = 2$. $c_y = 2$: Z Rotation Mode. 0.2726 Hz. $m_z = 10$. $c_z = 10$. The nominal closed loop poles are: Y translation. 0.0141 Hz. 35% damping: X translation. 0.042 Hz. 41% damping: Z rotation. 0.040 Hz. 40% damping.

The loop transfer function. the predicted closed loop versus open loop transmissibility and the sensor noise to acceleration spectrum is plotted for the stiffer Z rotation mode in Figures 8-9. These results are representative of all three modes.

6. CLOSED LOOP 3 AXIS GROUND EXPERIMENT

Control system was implemented part analog and part digital. Analog low-pass filters served the double purpose of attenuating the sensor noise and anti-aliasing. The control computer was an IBM Model PS/30(286). The accelerometer signals were sampled with an Analog Devices RTI-800 A/D converter. The control algorithm was implemented in Microsoft Quick C and ran at 18.2 Hz. The high-pass filter was realized digitally due to its very low time constant. The digital control signal was passed to the Analog Devices RTI-802 D/A output. The D/A output to the current amplifier drove the piezo-electric actuators.

First. we compare the open and closed loop transient responses. Figure 10 shows the three open loop accelerometer time traces recorded simultaneously for 40 seconds developed after a impulsive disturbance was applied (the experimenter blew on the inner box). The three

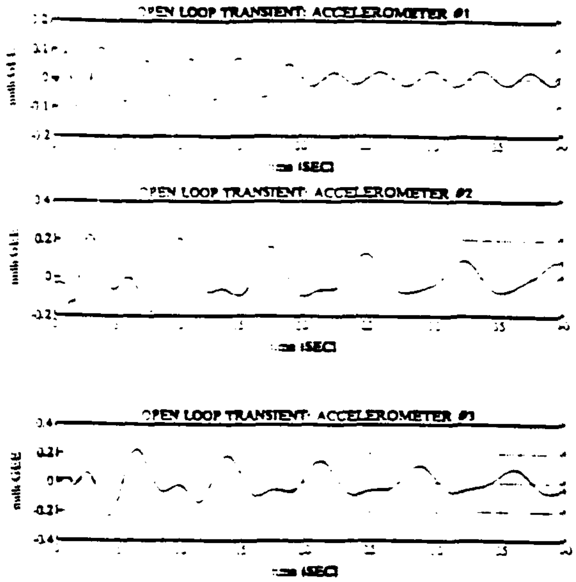


Figure 10: Open loop acceleration transient

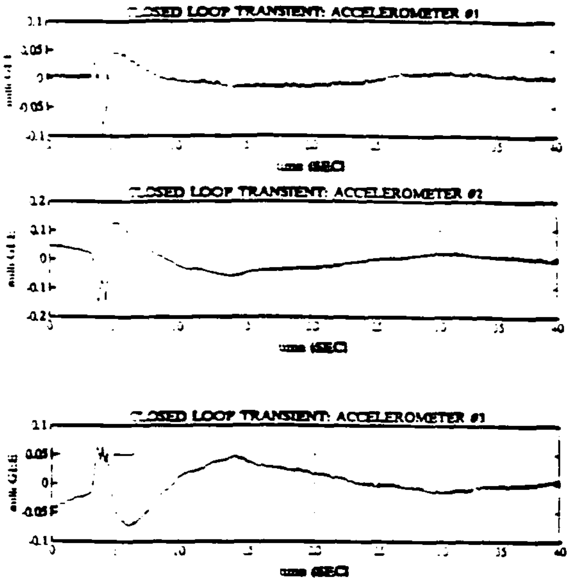


Figure 11: Closed loop acceleration transient

modes of the system are excited and damping levels are small. Figure 11 shows the three accelerometer time traces recordered simultaneously for 40 seconds with active control. The impulsive disturbance was applied to a corner of the inner box designed to to excite all three modes. The time period of the oscillation is close to 25 seconds, or 0.04 Hz. The motion is also more strongly damped.

Experimental transmissibility curves were also obtained. A single shaker was used to excite all three modes, Z rotation, X and Y translations. Shaker motion was measured by a LVDT displacement sensor. The transmissibility, or the transfer function between accelerometer output and LVDT output, was obtained using the Textronix Fourier analyzer. Transfer function units are Accelerometer Volt / LVDT Volt. The DC gain is not equal to 1 as predicted by the analytical model. Figure 12 compares the open and closed loop transmissibility for accelerometer #3. Note that the open loop natural frequencies have shifted due to the umbilical stretching over time, thereby increasing stiffness. Damping has greatly increased, and the closed loop natural frequency has decreased. The maximum attenuation seen in the transmissibility is observed at 0.3 Hz on Figure 12 where the attenuation is greater than 36 dB, or reduced by a factor of 70.

7. SUMMARY

The six axis microgravity isolation mount prototype developed at MIT is a practical solution to isolating vibration sensitive payloads on board milliGEE spacecraft such as the NASA space shuttle or space station. The isolation system can be visualized as two boxes. The inner box, containing the payload, is mounted to an outer box the volume of two NASA Space Shuttle middeck lockers. The inner box is attached to the outer box via several soft springs made of piezo-electric film, and soft utility umbilicals. The passive mechanical isolation is then enhanced actively using the piezo-film actuators. The payload has provision for cooling, datalink and power through umbilicals of limited stiffness.

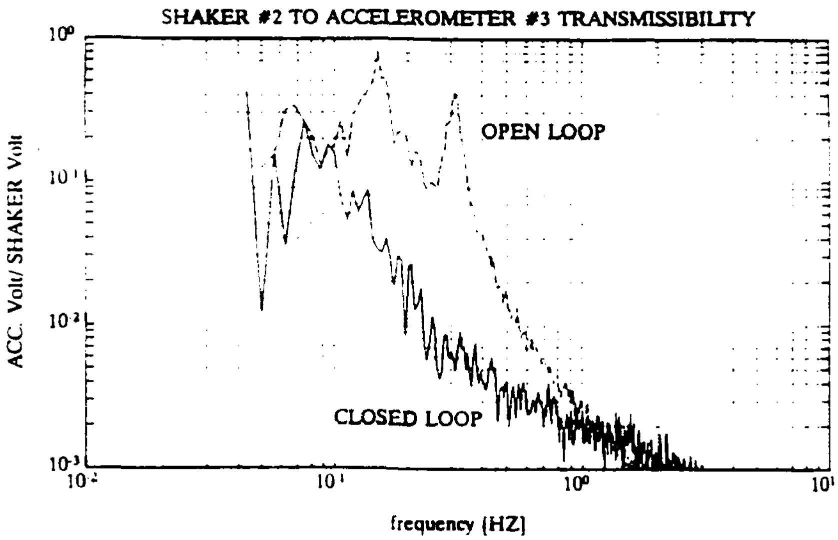


Figure 12: Comparison of experimental closed loop and open loop transmissibility between shaker no. 2 and accelerometer no. 3

The mount is designed to minimize interaxis coupling. Thus, ground-based system identification via three axis tests is sufficient to identify the six axis system, and provides enough information for control system design. The inertia and stiffness matrix are nominally diagonal and the location of the sensors and actuators makes modal control the natural approach. Active damping and mass are added to each mode via velocity and acceleration feeedback, respectively, such that the compensator is essentially a lag compensator. The control philosophy has been validated by the test performed on the 3 axis identification testbed.

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